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This study is concerned with measuring the cost of water supply and net revenue differences among customers by user class and location, and analyzing future water demand on the basis of plumbing permit application data. For water supply, a methodology based upon engineering principles was employed to collect data on distance, altitude, and costs of water delivery to sampled customers in a water utility service area. Estimates of cost elasticity were obtained. Altitude was not significant, but distance was found positively correlated with cost. In one location, at an extreme of the service area, this total cost elasticity became greater than one. Thus, cost economies for transmission of water exist, but are limited as indicated by this cost elasticity estimate. In addition, these costs were compared to the revenues collected from each customer sampled. The pattern of costs and computed net revenues were then examined through the use of computer mapping techniques. All this information becomes useful for examining water rates and system expansion.

Also examined is the hypothesis that future water use can be predicted through the use of plumbing permit records. It was concluded that the evidence for this same supply area does not support the hypothesis.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

In this report the authors have sought a better understanding of how water supply costs are related to the spatial features of the physical environment and how the costs of delivering water to water consumers compare with the revenues collected from them.

Francis T. Mayo, Director
Municipal Environmental
Research Laboratory

PREFACE

The continuing concern over the quality of the environment and the consequent search for ways to prevent further degradation as well as improve it inexorably leads to a closer examination of all human systems which affect and are affected by environmental quality. This report considers the case of urban water supply, a public service over which considerable concern has been raised about potential negative health effects resulting from waste discharges.

An examination of such issues inevitably raises questions about the incurred and opportunity costs of meeting water supply objectives. This in turn raises the question of alternative methods to reach the objectives, and of financing them. If the affected communities believe that the drinking water quality objectives are too costly to attain, they may reject the objectives. However, if the affected communities drinking water systems are not efficiently operated, i.e., at least cost, then policies designed to make explicit the cost of improved water to them may lead to unwarranted rejection of the drinking water standards. The inefficiency may make the cost of delivering improved drinking water higher than it needs to be.

Because of these kinds of considerations, studies of methods to improve environmental quality lead to an examination of the entire set of relevant sub-systems in order to find the least cost approach to the sought after improvements. This study is concerned with similar questions, and is focused on two basic propositions.

°It examines the intra-areal variations in the net revenues of water use in terms of cost-water rate differentials across an urban area.

°It seeks to explore how existing data collection activities at the local governmental level may be utilized by water system planners to predict water use, specifically plumbing permit data.

ABSTRACT

This study is concerned with the measurement cost of water supply, the measurement of net revenue differences among customers by class, and location, and the analysis of future water demand as revealed by plumbing permit application data.

Specifically, water supply functions are disaggregated respectively into (a) acquisition and treatment, and (b) transmission and distribution. From this, the cost of delivering water to various customers (by classes and specific users) are calculated as a function of distance, altitude and time of year (peak vs off-peak) for the Cincinnati, Ohio Water Works supply area. These costs are then compared with the revenues collected from the various consumers, and the net-revenues for each are computed, with the resulting variations displayed through computer mapping techniques.

Also examined is the hypothesis that future water use in the same supply area can be predicted through the use of plumbing permit records. It was concluded that the evidence from Cincinnati does not support the hypothesis.

This report was submitted in fulfillment of Grant No. R-803596-01 by the University of Cincinnati under the sponsorship of the U.S. Environmental Protection Agency. The work was completed as of January 15, 1977.

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SECTION 1

INTRODUCTION TO COST RATE DIFFERENTIALS

BACKGROUND

The metering and pricing of municipal water supplies is a wiedespread practice in the United States, with some important exceptions. There is also now widespread recognition of the impact that charging for water use has on the demand for water, both in residential and commercial-industrial uses. As a result, then, pricing can have a substantial impact on the requisite capital investment in acquisition, treatment and distribution facilities, especially if water pricing alternates peak demands.

For those water systems which do charge for their water, it is appropriate to ask which are the appropriate rate structures, especially with respect to delivering water under varying cost circumstances, as determined by distance, topography, and peak conditions. An inappropriate rate structure, while financing the system, can lead customers to utilize water in such a way so as to increase the quantity demanded, and thus create a "need" for more investment in expanding the system, thus making total and average costs unnecessarily higher, unless offset by scale economies.

It is, of course, necessary to have a definition of what constitutes an "appropriate" rate structure. The usual definition employed in cost-benefit analysis is to choose a rate structure (and thereby the quantity of delivered water given supply and demand conditions) that generates the maximum net benefits associated with water use. The usual first approximation this is to equate price (rate) to the incremental cost of delivery, or marginal benefit equals marginal cost.* Of course, this first approximation may be changed depending on the kinds of constraints added to the problem, such as the need to be self financing, even in the presence of scale economies.

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*See for example, A. Maass, et al., Design of Water Resource Systems, Harvard, 1962, Chapter 2.

For operational purposes, a water pricing policy which equates the rate (price) to the appropriately defined marginal cost of delivering water to a customer is the rate structure which will lead to maximum net benefits. This is generally termed "marginal cost pricing".*

The implications of this concept for our purposes is that if the rate is set less than marginal cost for some uses of water, then this water will be overused, in the sense that its value to the users will be less than its cost. The resulting increased demands, if not completely offset, will signal water supply officials that the water supply system needs to be expanded. An expanded system, however, would in fact be unwarranted.

Similarly, if rates are less than marginal cost for some customer classes and greater for others, it might seem that the effects would cancel out, with no net effect on the system. However, some users, particularly industry, are in better positions to economize on water use than others, as through water reuse, especially for process cooling and washing, such that the net effect would not be zero. Again, this can result in a system which is too large, and thus unnecessarily expensive.

This extra expense can take a number of forms, among which are:

1. excessive investment in all phases of water supply: acquisition, treatment, and transmission and distribution.

2. Operating costs, especially in treatment and distribution will be higher. A new element has also entered the picture: the discovery that surface waters contain potentially hazardous levels of carcinogens, of which removal is quite expensive (and the technologies are unproven). Excessive water use will mean excessive and expensive water treatment.

3. More water throughput means more sewage treatment, which is an expensive proposition for secondary and teritiary treatment. Policies which permit costs to be higher than they need to be (because of excessive water use) means that the public will demand less environmental quality, and be more accepting of lower water quality.

In addition to these cost considerations, there is the problem of equity. If water rates are less than the average cost (and the marginal cost) of supply for some water customers, this means that internal cross-subsidies among customer classes will be established. Such transfers can take a variety of forms: (1) there can be transfers between peak and off-peak users; (2) among customer classes (residential, commercial and industrial;) (3) between those near and those distant from the treatment facilities; and (4) between those at high altitudes and those lower. Such transfers violate common perceptions of economic justice or fairness, and may mean that the poorer members of a community subsidize the wealthier members. The evidence developed in this study on these questions will be presented below.

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*See e.g. Hirschleifer, deHaven and Millsman, Water Supply: Economics, Technology and Policy, University of Chicago Press, 1969, Ch. 5.

PURPOSE OF RESEARCH

The specific outputs of this research include the following:

1. Estimates of the costs of delivering finished water to customers in the Cincinnati Water Works (CWW) area, principally in terms of the main user classes (residential, industrial and commercial). Also, some evidence is presented for particular (unidentified) customers. Distance and altitude are analyzed explicitly as factors which determine costs.

2. Evidence on the nature and extent of cost-rate differentials, or subsidies along the dimensions mentioned above.

Three chapters follow:

1. An extensive review of the literature on the cost of water supply;

2. Methodologies used to compute the cost estimates developed in this study;

3. Empirical results, including estimates of costs and revenues, and the associated spatial distributions in the CWW system.

4. Conclusions and recommendations for future research.

The principal limitations of this study include:

1. An inability at the current level of analysis to detail more precisely the impact of distance on the cost of water supply. These impacts were measured for the average cost of supply, but not for total cost, as there are some statistical problems to be surmounted. As a result, this analysis needs more refinement in order to be able to separate out the implications for regionalizations of water supply systems.

2. Excluded from the analysis are the explicit impacts of provision of water for fire protection on the measured costs. It is included implicitly, however, through the cost allocations.

SECTION II

CONCLUSIONS AND RECOMMENDATIONS CONCERNING COST-RATE DIFFERENTIALS

In Section III we formulated six hypotheses concerning the relationships which were examined subsequently. We restate the hypotheses and summarize the empirical findings pertinent to them.

Hypothesis 1: Total water supply costs vary positively with distance and altitude. Statistical problems prevented a direct examination of the relationship between total cost, altitude and distance at this stage, but examination of the relationship between average cost, altitude and distance reveal positive effects. By implication, then, TC does vary positively with altitude and distance. Actual measurement of this effect requires more refined analysis.

Hypothesis 2: Peak period total costs exceed off-peak total costs. The results with respect to this hypothesis both support and do not support it, depending on the customer class, the region examined, and the variables included. Once the spatial aspects of costs are treated separately, it is quite possible for off-peak costs to be higher, as they are not offset by scale economics in acquisition and treatment (A&T). At the present level of understanding, it is not possible to determine whether there is a consistency among the pattern of results for peak and off-peak results.

Hypothesis 3: Scale economies in transmission and distribution (T&D) are mainly determined by industrial water demands, as opposed to commercial or residential demands. While the results obtained should not be regarded as conclusive, the findings in Table 14 suggest greater economies in residential supply as opposed to commercial or industrial supply.

Hypothesis 4: The Cincinnati Water Works earns revenue surpluses on customers close to the A&T facility, and incurs deficits on those farther away. For making statements about the questions of equity, it is best to use AC information to abstract from quantity variation. For the two routes examined, C_1 and C_3 it was found that (1) for residential users, the surplus tended in fact to be higher for the more distant users (Table 22) and (2) for commercial and industrial users, the reverse pattern of what was hypothesized (Tables 23 and 24).

Hypothesis 5: The CWW incurs revenue deficits on industrial and commercial water supply, and surplus on residential supply. Again, for comparisons on a unit basis, the findings in Tables 22, 23 and 24 tend to support this hypothesis.

Hypothesis 6: Peak period water users are subsidized by off-peak users. The findings in Tables 22, 23 and 24 do not support this hypothesis.

In general, the pricing structure chosen by the CWW does not fare too badly with respect to the analysis of a major variable, distance, in terms of the hypothesis that city residents (who tend to have lower incomes than the regional average) do not subsidize suburban residents (whose incomes tend to be above the regional average). However, the correspondence between rates and average delivered cost is weak, as measured by the methodologies developed here, although the system is self financing. Thus, there are cross-subsidies within the system. A realignment of rates would improve equity, if by equity we mean each customer paying his costs.

Suggested Research

The cost methodologies developed and utilized for this study are new, and considering that the level of effort was relatively modest, there are some refinements and improvements that need to be undertaken to improve the reliability, and the specificity of the technique. Additionally, although the resulting estimates do seem plausible and reasonable, it is desirable to develop methods of checking their accuracy. Thus, while the tools utilized do hold promise, the following should be done:

1. Closer investigation of the appropriate functional form for the estimates of the cost elasticities. While we chose our specifications based on the normality of various variable transformations, other criteria, such as $\bar{R}^2$, should be explored for the implications and impacts on the elasticities.

2. Population density is a factor which affects water supply costs, as has been found in other studies, and it should be introduced into this analysis.

3. In order to give more precision to the technique as a tool for rate setting purposes, more spatial detail or specificity needs to be introduced into the analyses in order to obtain a clearer picture of the spatial distribution of the cross-subsidies. This conclusion applies to peak and off-peak period analysis as well.

4. For the purpose of determining the economic boundaries to water supply systems, it is necessary to have a better understanding of its quantitative impact. It was not possible to determine the separate effect of distance on total cost within the framework of this study, but the data are useable for this analysis.

SECTION III

LITERATURE REVIEW ON THE COST OF WATER SUPPLY

INTRODUCTION

The costs of providing a safe and potable water supply for a regional and metropolitan area is becoming an increasingly important factor for water supply utilities. Expansion of the capacity to satisfy demand, as occurred in the 1940's, 1950's, and 1960's, may not be warranted due to excessive investment cost. In the 1970's and 1980's, future expansion must be carefully analyzed in terms of efficiency of resource use and the effect on total water supply costs, as well as adequacy of supply.

Increased costs are a major problem in the water supply industry. In 1965, capital requirements exceeded two billion dollars and were estimated to be about three billion in 1975.[a] Operating costs continue to increase as inflation persists.[b] Comprehensive analyses of costs are necessary to improve decision making. Without such research, decision on capital expansion and replacement, level and structuer of utility rates, and general operating procedure will be hampered. Adequate supply to meet water demand is an important factor, but knowledge of the costs to meet that demand are crucial.

PRINCIPAL COST COMPONENTS

In general, a water supply system's costs can be broken down into five major categories: acquisition, treatment, transmission, distribution,[c] and overhead. A brief synopsis of each follows.

---

[a] American Water Works Association - Staff Report. "The Water Utility Industry in the United States". Journal of the American Water Works Association, 58 (July, 1966), p. 781.

[b] In 1974, chemical costs at the Cincinnati Water Works increased over 100%.

[c] American Water Works Association - Staff Report, "The Water Utility Industry in the United States", p. 767.

The cost of acquisition involves the collection of raw water from a surface water source (lake or stream) or ground water source (well or spring). Pumping and plant facility cost, labor, and energy are the major portions of acquisition cost.

Treatment to produce a safe and palatable water supply can be very complicated or straight-forward, depending upon the input quality of the raw water and the output quality desired. Treatment generally comprises the following steps: settling, mixing of chemicals, flocculation, and filtration. Use of other processes for softening or removing iron or manganese are dependent on local management decisions. The costs of treatment are chemicals, sand, power, and depreciation on the physical plant.

Transmission pipelines are the major trunk lines used to transport large volumes of water. They connect the treatment plant to the pumping station, if gravity tunnels are not used, and the distribution system. Pumping stations, pipelines, and energy comprise the major costs of transmission.

Distribution works include the meters, pipelines, and storage facilities (water tanks) necessary to convey the water from the transmission system to the customer. A pumping station might also be involved if ground-storage exists. Therefore, distribution systems include the cost of pipelines, water towers, pumping stations, and energy.

The final category is overhead. Administration, interest on the debt, meter reading, billing, revenue collection, and the equipment involved are the major elements in this category. This is a highly labor intensive operation even though computers may be employed to speed work flow. The above five components represent a general breakdown of water supply costs.

In the following sections, two major issue areas are covered: methods of cost allocation, and water supply cost analyses.

METHODS OF COST ALLOCATION

This section reviews the issues surrounding the problem of cost allocation. Familiarity with this method provides a better understanding of the types of costs involved in water supply public utilities, and how they are related.

The basic principle of an allocated cost method is the "equitable" distribution[a] of costs to specific functions and customer classes. The American Water Works Association suggests two methods of allocating cost in their manual of water rates.[b] One is the commodity-demand method; the other is the base extra-capacity method.

Under the commodity-demand method, costs are divided into three functions[c] -- demand costs, commodity costs, and customer costs. Demand costs are directly related to the cost of providing system capacity to meet peak demands (i.e. maximum day, peak hour, or maximum week). This includes plant as well as operating expenses. Fire protection costs may also be covered here. Commodity costs vary directly with the quantity of water produced and sold. This involves the costs of power, chemicals, and other operating and maintenance expenses connected to the amount of water supplied. Customer costs consist of expenditures on meter readings, billing, accounting and collecting, meters, and maintenance of customer related equipment (billing machines and meters). Those costs vary with the number of customer accounts, but are independent of the water produced or the demand rate.

The commodity-demand method is one approach to the allocation of utility costs to specific functions. The other prominent method is the base extra-capacity method. R.L. Greene notes that this breakdown "is the one generally accepted in the field."[d] All costs are again divided into three components:[e]

---

[a] Equity here is not similar to an economic concept of equity, where income distribution becomes important. Rather, it refers to economic efficiency where the price paid approximates the cost incurred.

[b] American Water Works Association. Water Rates Manual. (New York: American Water Works Association, 1972. Second Edition).

[c] The three components of the commodity-demand method are easily classified into fixed or variable costs, traditional economic cost concepts. Demand costs represent fixed costs, while commodity and customer costs comprise variable costs. Customer costs are variable, since they cease if output stops.

[d] R.L. Greene. The Economics of Municipal Water Rates. Unpublished Ph.D. dissertation, University of Florida, 1968.

[e] In the base-extra capacity method, the three components are not easily classified as fixed or variable. Customer costs remain variable as before, but base and extra-capacity costs both contain fixed and variable elements. This results from the use of average daily demand as the demarcation between base and extra-capacity.

customer, base, and extra-capacity. The definition of customer costs is the same as for the commodity-demand method. Base water costs are the costs associated with the quantity of water demanded and the operation, maintenance, and capital costs of servicing the average daily demand on the system. The average daily demand is identified as a 100% load. In this component, operating costs are joined with capital costs, while only operating costs comprised the commodity component above. Extra capacity costs consist of the costs to meet use requirements above the average 100% load. It includes capital and operating costs for additional system capacity beyond the average, such as the maximum hour or day.[a]

Once costs have been allocated to the correct functions, the proper appointments to customer classes remain to be determined. Briefly, allocation of capacity or demand costs to customer classes[b] are decided primarily on the basis of ratios of peak demands to average demand. Commodity or base costs are distributed according to the volume of water used. Customer cost allocation, though, depends on the number of customers or meters. The AWWA theorizes that equity is approximated if a rate structure attempts to recover costs allocated in this procedure.

Linaweaver and Geyer[c], in a study on residential water use, appear to promote the base extra-capacity method. They discuss how part of the John Hopkins University Water Research Project is attempting to gather data on peak use by customer class which may prove useful in the allocation of extra-capacity costs. But, they do question one point in this type of allocation, namely, the use of average annual consumption in determining the proportion of plant investment to be allocated to base capacity.[d] Average daily use fluctuates around average annual use. During the winter, average daily use is lower than the average annual; but it is higher during the summer. Rather, Linaweaver and Geyer suggest the use of domestic water requirements, average daily winter demand, to determine base costs.

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[a] Fire protection costs may also be included.

[b] The major customer classes are residential, commercial, and industrial users. Sometimes, special cases are considered as hospitals, schools, government buildings, and welfare cases, but they are ignored here.

[c] F.P. Linaweaver and John Geyer. "Use of Peak Demands in Determination of Residential Rates". Journal of the American Water Works Association, 56 (April, 1964), p. 403.

[d] Ibid, p. 405.

Also, sprinkling demand can be identified and used for the extra-capacity cost allocation. As far as residential water demand is concerned, that seems more equitable than use of average annual demand for cost allocation.

Another proponent of the base extra-capacity cost method is W.L. Patterson.[a] His article on water rates in 1962 is widely quoted as the major article in this field. Patterson provides an extensive example of cost allocation, using the base extra-capacity method to allocate system costs and noncoincidental extra capacity method to distribute peak use costs to customer class.

A noncoincidental method implies that the peak characteristic (ratio of maximum use to average annual use) of each class be examined. The term, noncoincidental, signifies that the ratio of peak to average is not related to the time of the system peak. If a certain customer class did not consume during the system peak time, but was characterized by a high ratio of peak to average use at another time, then part of the system capacity costs would be allocated to that customer class. Patterson notes that:

> "this method of allocation most equitably distributes costs among customer classes whose individual maximum demands would not necessarily occur simulatneously or at the time of the system peak."[b]

The actual degree of equity in this and other forms of peak load cost allocation is an issue that has received much attention in the literature.

Davidson, in his book on price discrimination, devotes a full chapter[c] to all the proposed methods of capacity cost allocation. In brief, he demonstrates that all twenty or more methods, including the noncoincidental method, possess varying degrees of discrimination. One or another group of customers can force a reallocation of costs from themselves to others by adjusting their demand loads, even though their load contributes to the system peak. As a result, the noncoincidental method is shown to increase discrimination among users if rates are based on such a cost allocation.

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[a] W.L. Patterson. "Practical Water Rate Determination". Journal of the American Water Works Association, 54 (Aug., 1962), p. 904-12.

[b] Ibid, p. 909.

[c] Ralph K. Davidson, Price Discrimination in Selling Gas and Electricity, (Baltimore: John Hopkins University Press, 1955), Chapter 8.

Davidson applies the commodity-demand method in his analysis, but adds one important point: the relevant costs. The relevant cost concept

> "is not the expost accounting record of costs incurred in producing, distributing, and selling the (commodity) purchased by the consumers in a period just past. All attempts to ascertain unambiguously total costs, or average costs per unit of output from ex post accounting records encounter insuperable difficulties in the allocation of fixed costs, common costs, and joint costs; these costs are arbitrarily allocated, if they are allocated at all. This particular problem of allocation of fixed, common, or joint costs is not encountered in finding marginal or incremental costs, but it is also true that marginal or incremental costs cannot be determined from usual accounting records. The usual accounting records are records of the past and the relationship with which economists are concerned are the expected or anticipated relationships--a matter of the future."[a]

Marginal or incremental costs, if possible to determine, are the relevant costs. Davidson theorized that the important elements to be defined are the additional costs incurred if another unit of output is sold, the incremental cost of an additional unit of capacity for peak load demand, and the marginal cost of another customer served by the system. Employment of these definitions of costs would improve resource allocation and avoid some of the problems of a strict cost allocation.

Davidson also mentions the problem of allocation under conditions of joint and common cost. Though not directly discussed by Davidson, other articles have elaborated on it. Greene[b] criticizes Patterson's work and discusses the problem of joint cost. He argues that the ratio (noncoincidental) method of cost allocation used by Patterson favors large quantity users more than other users, since the larger ones have a higher average hourly use than the smaller customers. It also tends to penalize users, with or without a peaking characteristic, who do not take water during the system peak. A cost allocation based on Patterson's method would distribute cost on the basis of differences in demand characteristics rather than differences in costs imposed by the various user classes. This does not lead to an equitable allocation if rate differentials are based on this allocation.

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[a] Davidson, Price Discrimination in Selling Gas and Electricity, (Baltimore: John Hopkins University Press, 1955), p. 69.

[b] Greene, The Economics of Municipal Water Rates, p. 110.

According to Greene, the cost allocation methods were derived because of the joint cost conditions between peak and off-peak conditions. Capacity costs are joint costs if the cost of producing the services (joint products) is rendered at different periods of time.[a] Time jointness is the correct term. Capacity which is used to meet a peak demand, is also available for off-peak use. Services produced at those different times are true joint products because capacity cannot be adjusted. Greene points out that the utility solution to joint cost conditions (Patterson approach) implies that the distinct customer class demands are summed vertically, (Figures 1 and 2), to determine the distribution of costs to each consumer group on the basis of relative demand strengths. The vertical summation requires that each class be allocated a different per unit cost of capacity, depending upon the relative heights of their demand curve, even if the customer classes were to consume identical quantities of the commodity in the same time period. If the demands were summed horizontally, as in Figure 2, the same per unit charge could be allocated to each customer class, but the total cost allocated would vary because the quantity consumed by each group in the same time period is not the same.

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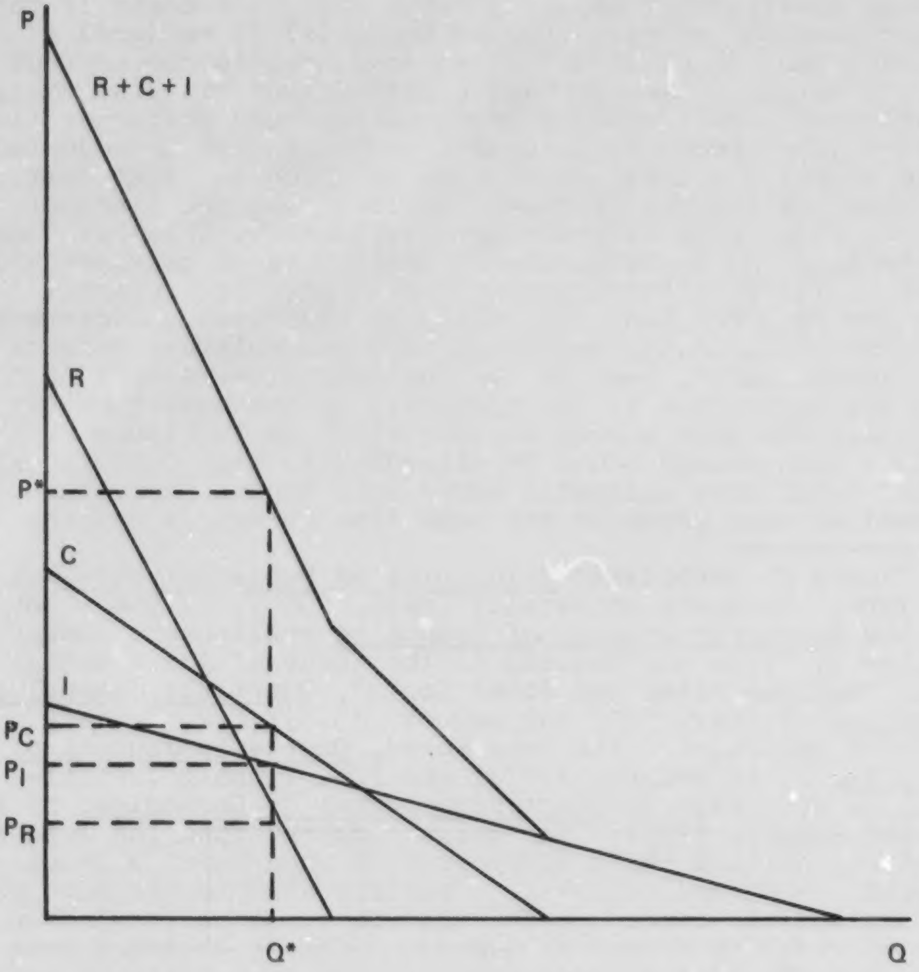
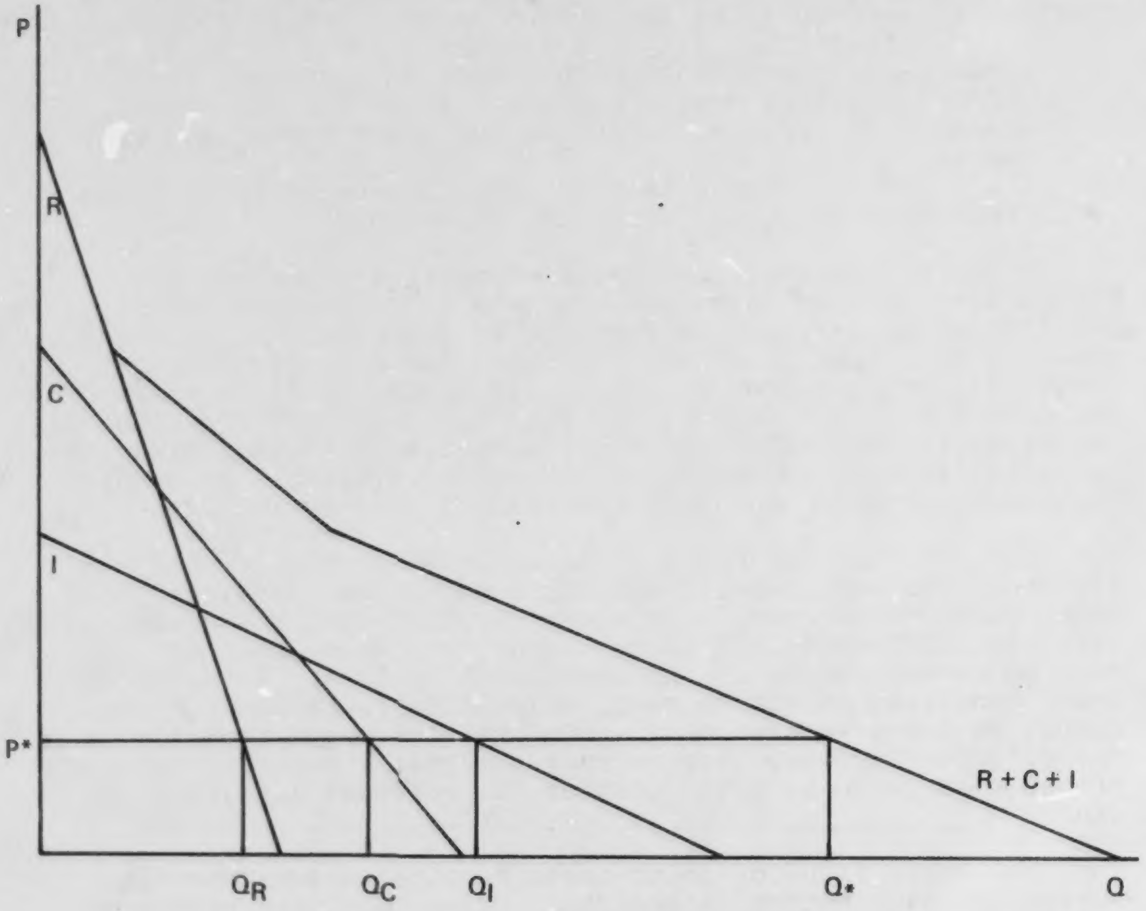
[a] James C. Bonbright, Principles of Public Utility Rates, (New York: Columbia University Press, 1969), p. 354. Note that the Quarterly Journal of Economics published a number of articles by Pigou and Taussig on the issue of joint costs: A.C. Pigou, "Railway Rates and Joint Costs", Quarterly Journal of Economics, 27 (May, 1913 and August, 1913); F.W. Taussig, "Railway Rates and Joint Costs Once More", Quarterly Journal of Economics, 27 (February, 1913); and F.W. Taussig (Untitled rebuttal to A.C. Pigou), Quarterly Journal of Economics, 27 (May, 1913 and August, 1913). The issue centered upon the separability of certain costs of production when joint products were produced. Wool and mutton is a classic example of joint products with unallocable costs. Cost, therefore, was allocated on the basis of relative forces of demand. Taussig believed that principles of joint product pricing were applicable to railroad rate setting, while Pigou opposed such an adoption.

In a more recent article, R.L. Weil, Jr., "Allocating Joint Costs", American Economic Review, 58 (December, 1968), p. 1342-45, a mathematical model which allocates joint costs is presented. His allocation is based on the idea that joint cost allocations equal marginal revenues and are determined in part by conditions of demand.



Q* = plant capacity.
P* = weighted average of $P_C + P_R + P_I$.
R = residential demand curve.
C = commercial demand curve.
I = industrial demand curve.
P_R = residential price.
P_C = commercial price.
P_I = industrial price.

Figure 1. Vertical summation of demand curves.



Q^* = plant capacity
P^* = price per unit
Q_R= residential demand at price P^*
Q_C= commercial demand at price P^*
Q_I = industrial demand at price P^*

Figure 2. Horizontal summation of demand curves.

It would depend on the demand curve of each separate class. This is a more realistic description of the peak-load situation when characteristics of consumer classes are considered.

The principle foundation to Greene's argument is the distinction between joint and common costs. Greene states,

> "there is no justification for charging different users, in the same time period different rates for the same quantity of service, since the costs are common costs and not joint costs.
> . . . Any difference is discrimination based on criteria other than economic efficiency criteria."[a]

Wallace presents, in a rather lengthy discussion, the distinction between joint and overhead costs (common costs). Briefly, he argues that in the case of joint supply, productive capacity available is fixed in proportion to the demands of different customer groups. An entrepreneur cannot increase or decrease his output capacity in one market without affecting the capacity available in another market.[b] This is similar to the situation of a water works. Capacity available to handle peak-load operation is available for off-peak periods.

But, if capacity may vary in relation to the demands of different customer groups, cost is common. For services produced with common cost, no element of jointness, uniformity in rates is appropriate. This may occur in a water utility when many consumers demand at the same point in time. As a result, under condition of common cost, allocation to consumer groups cannot be made, because cost is not related proportionally to the different groups. For correct analytical results, Wallace promotes long-run marginal cost as the relevant dimension to study.

The basic issue of joint costs revolves around the time period in which output is consumed. Time jointness refers to the fact that capacity cannot be adjusted to meet changing demand. Peak demand is responsible for the amount of capacity available. Off-peak demand is serviced with excess capacity. Therefore, cost should be allocated differently between these periods. An off-peak unit, consumed by a residential customer, costs differently than a peak unit.[a] As a result, cost allocation, according to Greene, Wallace, and Bonbright, should depend on the time jointness of the costs. Changes in demand rates require different cost allocations between peak and off-peak regardless of the relative strengths of demand at a given point in time by each customer class. Once the peak has been reached, the capacity cost per unit of output is the same whether a residential, commercial, or industrial user consumes the service.

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[a] Greene, The Economics of Municipal Water Rates, p. 114.

[b] Donald H. Wallace, "Joint Supply and Overhead Costs and Railway Rate Policy," Quarterly Journal of Economics, 48 (August, 1934), pgs. 584-586.

The issue of cost allocation still remains. Bonbright notes that the main reason for difficulty with the full-cost apportionment method:

> "lies in the special character of the only costs that can be allocated, on a cost causation basis, to specific quantities of specific types of service."[b]

The costs that are allocable are of necessity the differential, incremental, or marginal costs. Bonbright also points out that only rarely would these costs sum up to total operating and capital costs.[c] Other cost allocation deficiencies discussed by Bonbright[d] are the inability to define fair value of capital[e], investment for peak load allocations, the failure of the cost analyst to allocate all costs to three or four categories, and the poor handling of joint cost issues by the cost analyst.

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[a] These are the same results implied but not as explicitly stated in articles by Steiner, Hirshleifer, and Williamson, on peak load pricing where the peak user alone pays for capacity costs and common costs are not allocated by customer classification. See: Peter O. Steiner, "Peak loads and efficient pricing", Quarterly Journal of Economics, 71 (November, 1957), 585-610; Jack Hirshleifer, "Peak loads and efficient pricing: comment", Quarterly Journal of Economics, 72 (August, 1958), 451-62; and Oliver E. Williamson, "Peak-load pricing and optimal capacity under Indivisibility Constraint", American Economic Review, 56 (September, 1966) 810-27.

[b] James C. Bonbright, "Fully Distributed Costs in Utility Rate Making", American Economic Review, 51 (May, 1961), p. 307.

[c] This occurs because of the existence of returns to scale.

[d] Bonbright, Principles of Public Utility Rates, p. 367.

[e] This refers to the discussion over the use of historical or reproduction costs or the fair value of capital.

Like Wallace and Davidson above, Bonbright favors an estimation of the long run marginal costs to service different classes and a formula apportionment among the classes for all unallocable residues of total cost. This could free the analyst from pressure to divide up all the costs, even though there would still be problems in finding a rational method to apportion the unallocable residual costs. Bonbright concludes that,

> "the really important analyses are not those which attempt to apportion total capital and operating costs among the different classes or units of service. Instead, they are the analyses designed to disclose differential, incremental, or marginal, or escapable costs--costs which are not ordinarily derivable from total costs and which cannot be added together so as to equal this total."[a]

In their excellent book on water supply, Hirshleifer, DeHaven, and Milliman also discuss the issues involved with a cost allocation method. They argue that because of the existence of joint costs, there is no unique way to segregate total costs into three components: customer, commodity, and capacity.

> "This is logically equivalent to the impossible task of dividing sheep costs into wool costs, mutton costs, and hide costs. A new reservoir, for example, may at one stroke increase system capacity, permit connection of a new class of consumers, and lower unit costs of delivering the commodity."[b]

With regard to capacity allocation, Hirshleifer, DeHaven, and Milliman, believe that capital costs cannot be correctly divided between the various service dimensions represented by capacity and commodity. Any attempt to do so, as exemplified by the Water Rates Committee of the AWWA, is defective in theory and inconsistent in application.[c] This also applies to the general classification of costs under the commodity-demand method.

Their alternative is identical to that offered by Davidson, Wallace, and Bonbright. The relevant dimension to examine costs is the marginal cost: the cost of adding another customer with capacity and commodity elements constant; the cost of adding a unit of capacity with customer and commodity elements constant; and the cost of increasing output by one unit with customer and capacity elements constant. Those costs are measurable and more relevant for rate purposes. In another article, Milliman points out that,

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[a] Ibid, p. 363.

[b] Jack Hirshleifer, James C. DeHaven, and Jerome W. Milliman, Water Supply: Economics, Technology, and Policy, (Chicago: University of Chicago Press, 1960), p. 98.

[c] Ibid, p. 99. Note: Some arbitrariness may be required. It is not easy to classify what is incorrect, if no correct way exists.

> "Pricing according to incremental costs, water rates that reflect true economic scarcities, must become the order of the day if we hope to deal with the problem of water supply in the future."[a]

In general, this discussion on allocation of costs has attempted to outline some of the problems associated with current practices in use and the correct way to examine costs. Though there has been no final solution to the issue, the present state of the literature appears to favor the Davidson, Bonbright, Wallace, Hirshleifer, DeHaven, and Milliman analysis of costs to the AWWA or Patterson approach because of the latter's misinterpretation of the joint vs. common cost issues.

WATER SUPPLY COST

This section reviews existing literature on water supply cost functions and analyses. In estimating statistical cost relationships, two different approaches stand out as the most significant.[b] One is a factor-cost approach; the other is an explanatory variable approach.

The factor-cost approach develops a statistical relation between total cost and the price and quantity of the factors employed. This type of cost function can be defined if the production relation, quantities of inputs, and prices of inputs are known. One major difficulty with this method is the identification and estimation of the production relation. Also, the cost function developed tends to be more of an accounting relation than an economic one.

The other method is an explanatory variable approach. This method attempts to estimate the statistical relationship between cost and certain key explanatory variables. A general functional relation is theorized, the specific form of which is determined by the interdependencies among the variables. A functional cost relation can be stated as $c = f(x)$ or $f: x \rightarrow c$ where c is cost (total, average, or marginal) and x is a vector of explanatory variables and shift parameters.[a] The form may be linear or nonlinear. The statistical relation does not attempt to examine cost in actuality for accounting purposes. Rather, the explanatory variable approach tries to identify the interrelationships that exist to improve predictive and explanatory capability. This is the direction that this discussion will follow.

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[a] Jerome W. Milliman, "Economics and Water Supply", Water and Sewage Works, 110 (Reference number), p. R-16.

[b] J. Johnston. Statistical Cost Analysis, (New York: McGraw-Hill, 1960), Chapters 2 and 3.

Three major categories exist in the literature on water supply cost. They are treatment, total cost, and transmission cost. One brief look at peak-load cost will be included, but it is not as important because no articles appear to concentrate on peak-load cost estimation.

Treatment Cost

Two main elements which comprise treatment cost are analyzed. One is construction or capital cost; the other is operation - maintenance cost. Orlob and Lindorf[b] examined treatment cost to determine its relationship to the costs of surface water importation, reclamation of waste waters, ground water recharge, and any other alternatives available for increasing water supply to California. Their study consists of a cross-section of 32 treatment facilities as existed in 1956 in California.[c] All construction cost data was adjusted by means of a water treatment plant construction cost index. Based on the *Engineering-News Record* Construction Cost Index and the Marshall and Stevens Equipment Cost Index, they developed their own index for the Pacific Coast States. The treat plants included were only those with complete treatment.[d]

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[a] The factor cost approach could be modeled as follows: $C = \sum_{i=1}^{n} r_i X_i$ where C = total cost; r_i = price per unit of the (i)th factor; and X_i = amount of the (i)th input purchased.

[b] G.T. Orlob and M.R. Lindorf. "Cost of Water Treatment in California," *Journal of the American Water Works Association*, 50 (January, 1958) p. 45-55.

[c] Since this is a cross-sectional analysis, the long-run cost curve is generated. See Johnson, *Statistical Cost Analysis*, Chapter 5.

[d] Orlob and Lindorf, "Cost of Water Treatment in California", defined complete treatment as including "at least flocculation, sedimentation, rapid-sand filtration, and chlorination. Aeration or special chemical treatment, such as softening or taste and odor control were not common to all plants", p. 47. Use of other processes or technology will affect shape of cost curve.

Construction cost was theorized as a function of the explanatory variable, design capacity. In general, the form of the equation would be:

$$C = \alpha Q_n^{\beta}$$

where C = total capital cost of a complete water treatment facility;

Q_n = the design capacity of the plant in million gallons per day (MGD); and

α = intercept

β = elasticity of total cost with respect to design capacity.

Estimation of the equation generated this relationship:[a] $C_c = 257\ Q_n^{0.67}$. The value of $\beta = 0.67$ implies that economies of scale may exist in treatment plant construction. If t-statistics were provided, it would have been possible to test whether β is significantly different from one. Since the relevant statistics are not available, no conclusion can be made concerning economies of scale.

Operation and maintenance cost is assumed to be related to average daily flow in million gallons per day in the same functional form as construction to design capacity above. The statistical relation estimated by Orlob and Lindorf[b] is:

$$Co = 68.4\ Qa^{-0.41}$$

where Co = the cost of operation and maintenance (including labor, chemicals, power, and plant overhead); and

Qa = the average daily flow, MGD.

This is an average cost function, not total cost. The dimension of Co is ($/million gal.). Converted to total cost, $C = 68.4\ Qa^{0.59}$. Since $\beta = .59$, economies of scale may also exist in the operation and maintenance of treatment plants.

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[a] No R^2 or t-statistics were provided. Note: construction cost expressed as cost per million gallons per day of design capacity as derived from the estimated total cost equation, is $Cc/Q = 257\ Qn^{-.33}$.

[b] Again, no R^2 or t-statistics were provided.

The importance of their work is not the statistical merit, but the fact that it is one of the first attempts to estimate the costs of water treatment. The authors ignored discussion of the issues of economies of scale. Instead, they concentrated on determining the relation of treatment costs to the production costs of all plausible alternatives for water supply expansion. As a result, important economic issues were not examined.

In a more recent article, L. Koenig[a] further investigates the area of water treatment cost estimation. He attempts to provide a detailed analysis of the physical characteristics, operating data, and costs of a water treatment plant. Once the information is presented in a standardized form, comparisons may be made between plants.

The general objective of Koenig's study was to identify the relevant costs of water treatment and their proportional contribution to total cost. The purpose was to provide data and information to decision-makers, such as utility managers, engineers, planners, and economists, and to aid in cost-benefit analyses.

This study is based on the cost engineering audits of 30 water treatment plants as of 1965. The sample data is a representative cross-section of water purification plants.[b] The methodology employed is similar to that used by Orlob and Lindorf in that a cost index was used to adjust investment expenditures to one common year. But Koenig expanded his study to examine in detail specific treatment costs such as: chemical, filter, energy, heating, and manpower costs as well as capital expense. With respect to investment expense, Koenig estimated an equation similar to the one Orlob and Lindorf used. The only difference is that Koenig's is an average cost relation. He finds that:

$C = 30.7\ Q_d^{-0.323}$ (with a correlation coefficient = 0.768 and significant from zero at the .001 level) where Q_d = design capacity; and

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[a] Louis Koenig. "Cost of Water Treatment by Coagulation, Sedimentation, and Rapid-Sand Filtration", Journal of the American Water Works Association, 59 (March, 1967), p. 290-336.

[b] The class of water treatment plants studied by Koenig differs from those examined by Orlob and Lindorf. Koenig included those plants having coagulation, sedimentation, and rapid-sand filtration. Orlob and Lindorf include the chlorination process in their plant description.

C = cost, ¢/gpd.

Orlob and Lindorf found the total capital cost relationship: $Cc = 257\ Qn^{0.67}$ which upon conversion to an average cost function became $\bar{C}c = 257\ Qn^{-0.33}$. The value of the exponent of Q is nearly equal in both. Koenig continued his analysis by adding Orlob and Lindorf's data to his. The combined regression provided a correlation coefficient of 0.57 and a line flatter and below the line estimated from Koenig's data alone. The difference, according to Koenig, is the several small plants with exceptionally low investment costs which were included in the Orlob-Lindorf study. As a result, their data was dropped in Koenig's subsequent analyses.

Instead of estimating an operation-maintenance cost equation, Koenig estimated average total cost for complete treatment for different utilization ratios. A utilization ratio, $\bar{U}$, was defined as the ratio of average raw water intake in MDG, $\bar{Q}$, to the design capability for raw water in MGD, Q_d. Total costs were computed for each plant at $\bar{U}$ = 0.2, 0.5 and 1.0, the Q_d lines in Figure 3. A statistical regression was then performed relating $\bar{Q}$ and unit total costs at each $\bar{U}$ value to derive the $\bar{U}$ lines in Figure 3. All showed high correlation coefficients, but unfortunately, Koenig did not provide the parameter estimates or the specific form of the regression. He did include a graph of the function, Figure 3.[a] From this, one can roughly estimate the total treatment costs of various size plants and average daily flows.

An interesting factor that Koenig fails to point out is the existence of economies of scale. His regression line of investment costs and the functions estimated, as shown in Figure 3, both point to the existence of positive economies of scale in treatment plant investment and operation-maintenance. He discusses methods of cost reduction and the contributions to cost of key inputs as manpower, but appears to have ignored any discussion of economies of scale. This probably can be attributed to the fact that Koenig's objective was to improve data acquisition and estimation of treatment costs and not to investigate for economies of scale.

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[a] The Qd lines in Figure 3 resemble short-run average total cost lines and the $\bar{U}$ lines resemble long-run average total cost lines. The graph is from Koenig, "Cost of Water Treatment by Coagulation, Sedimentation, and Rapid-Sand Filtration", p. 327.

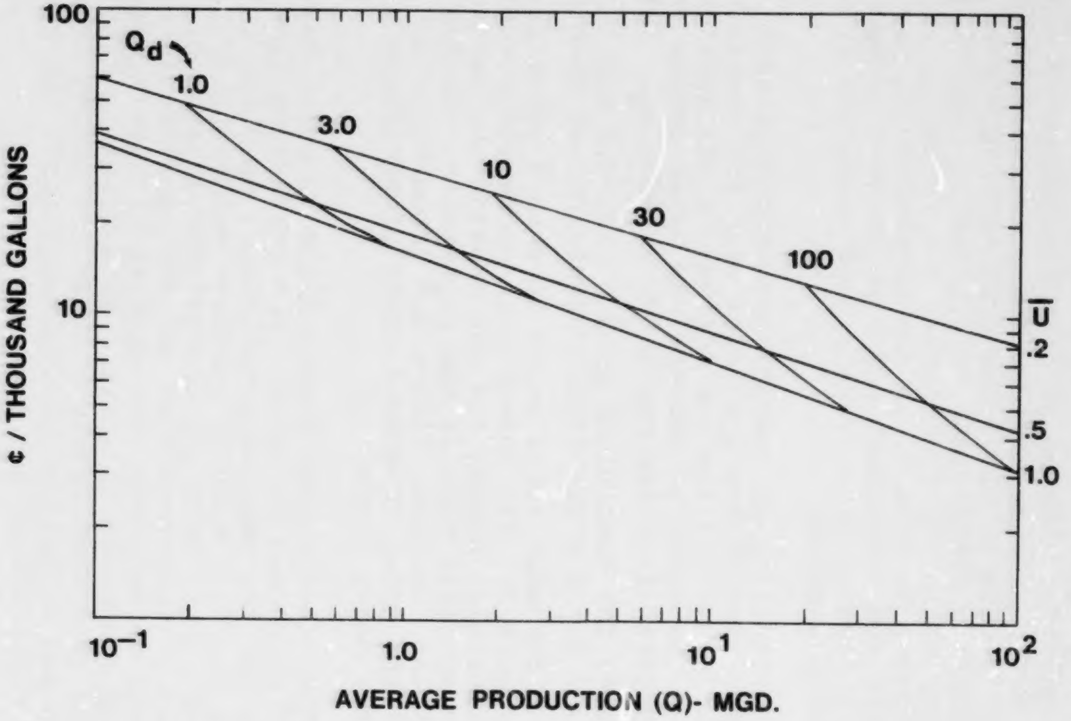

Figure 3. Median total cost of treatment.

One other article examines treatment cost. Hinomoto estimated unit and total cost functions for water treatment based on Koenig's data. A formula is developed to estimate the total annual cost of surface water treatment incurred by the plant of a given capacity operated at a given use rate. This formula is derived from seven regression equations on the major factors of water treatment: capital investments, chemicals, pumping energy, heating energy, manpower, maintenance and repair, and miscellaneous. Non-linear functional forms of the type $C = \alpha K^{\beta}$ (total cost) or $C/K = \alpha K^{\beta-1}$ (average cost) are specified for all seven equations. A logarithmic transformation was performed to permit linear estimation of the regression relationship. The estimated unit cost functions obtained are:

Capital Investment $= U^{-1}(81.9SK^{-0.325})$

Chemicals $= 1.20\ K^{-.236}$

Pumping Energy $= 2.78\ K^{-.282}$

Heating Energy $= U^{-1}(.307K^{-.519})$

Manpower $= U^{-1}(2.73K^{-.313})$

Maintenance and Repair $= U^{-.5}(.405K^{-.421})$

Miscellaneous $= U^{-1}(.102K^{-.07})$

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[a] Hirohide Hinomoto, "Unit and Total Cost Functions for Water Treatment Based on Koenig's Data", *Water Resources Research,* 7 (October, 1971) p. 1064-69.

where U = the daily use rate[a], output divided by design capacity;

S = the annual amortization factor (fraction of plant to be depreciated); and

K = design capacity.

Hinomoto combines all seven equations to define a total per unit cost equation for a treatment plant. Therefore, given a K, S, and U, the total unit cost can be obtained.

Again, no mention of economies of scale is made. Also, Hinomoto points out that he obtained results very close to Koenig's which is not surprising since he used Koenig's data and methodology. The merit to Hinomoto's analysis rests upon his rigorous use of the U variable.

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[a] Hinomoto estimated the relationship $C/K = \alpha K^{\beta-1}$ for all seven equations. But, certain of the variables (capital, heating, manpower, maintenance, and miscellaneous) are indirectly related to U, while chemicals and energy vary directly. The assumption is that capital, heating, manpower, and miscellaneous are fixed costs. Therefore, as U increases, C/Q would decrease, $C/K = \alpha K^{\beta-1}$ can then be converted to $(C/K)/U = \alpha K^{\beta-1}/U$

or

$C/Q = U^{-1} \alpha K^{\beta-1}$

since

$U = Q/K$

where Q = quantity of output produced. Maintenance expense was assumed by Koenig and Hinomoto to vary indirectly with $U^{0.5}$ because maintenance and repairs presumably contain fixed and variable elements of cost. Choice of .5 is arbitrary.

Finally, the equations for chemical and energy do not contain U since cost increases in direct proportion to an increase in output.

The use of U by Hinomoto is unusual in that it is incorporated into the equation after the empirical relationship is determined. It actually appears as a constant. One explanation for the approach may be attributed to the formula-type results generated. Hinomoto has attempted to develop a formula for the estimation of the cost of water treatment. Given a U and K, C/Q can be derived. That is a different way of establishing a relation than statistically estimating the relation of all the variables.

In general, treatment cost studies have concentrated on estimating the relationship of cost to design capacity and improving the generation of data for better decision making. The Orlob-Lindorf study began the analysis of treatment cost with a simple relationship. Koenig improved the structure of the analysis by incorporating the utilization factor. Hinomoto extended the use of the U in his set of statistical equations. The next step to be taken in this field appears to be the estimation of costs on a process oriented basis. Instead of estimating the costs of each input, estimate a relationship between cost of flocculation or filtration with respect to a key explanatory variable.[a]

Total Cost

This section reviews the existing literature on total costs of water supply. Total cost of water supply suggests two major divisions: treatment and transmission/distribution. Briefly, treatment involves purification of water; and transmission/distribution consists of finished product transportation to the consumer.

The difficulty of analysis on total cost arises in correctly identifying variables that are related or explain the variation in costs. Coase,[b] in his article on uniform pricing systems, examines the shape of the supply and cost curves when the same price is charged for a product or service over a given area, even though the cost of supply may vary from one part of the area to another.[c] If a public utility is to be self-supporting, and a uniform price is adopted, then if

> "the additional costs of supplying certain groups of consumers exceed the receipts obtained from those consumers, the difference will have to be made up by additional payments from other groups of consumers."[d]

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[a] Peak costs of treatment is another aspect for further research. Treatment plants may be designed for the average day or maximum day depending upon the local demand characteristics. In either event, a peak-load can exist in the treatment process. Analysis of this peak cost is needed to improve the basis for a rate structure.

[b] R.H. Coase, "The Economics of Uniform Pricing Systems", Manchester School of Economics and Social Studies, 15 (May, 1947) p. 139-56.

[c] See also: Robert H. Nelson, "Economies of Scale and Market Size", Land Economics 48 (August, 1972), p. 297-300.

[d] Coase, "The Economics of Uniform Pricing Systems", p. 140.

In his discussion, Coase assumes that the marginal costs of supply to each consumer rise with an increase in distance from the plant and that the marginal costs of supply to each individual consumer are constant at a given distance from the production source. As a result, the shape of the cost curve depends upon the quantity consumed by individuals at various distances from the plant. This is exemplified in Figure 4.[a] Line (1) would be obtained if consumer demand at each cost/distance level is relatively large compared to that in line (2) or line (3). Total cost can be dependent upon many factors. Coase points out two: quantity supplied and distance. Even though the price charged appears to affect the shape of the cost curve, it is the marginal costs at each demand level, not price, that are important. Other explanatory variables are used in several empirical studies.

L. Hines[b] attempts to estimate a long-run cost function based on a cross-section sample of Wisconsin community water supply systems.[c] Since a long-run cost function is estimated, certain issues must be handled. Equipment and operating costs must be converted to the same price level using a cost index. The adjusted capital expenditures have to then be depreciated at a rate reflecting the remaining capital value. Estimates of capacity are necessary to make comparisons among different installations, because one plant operating near capacity may have lower per unit costs than one producing lesser capacity. A competent measure of scale is very difficult to obtain.

Hines estimates the relationship of cost to per cent capacity utilization (% Cu) and adjusted plant investment (API) for three production classes: surface water supply, ground water supply, and ground water supply with partial treatment. Two cases in each class are specified with respect to adjusted plant investment: API_1 = historical plant cost adjusted to the

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[a] Ibid, p. 142. An implied assumption is that a utility sells more, the further it extends it service area, which is not an unrealistic assumption.

[b] Lawrence G. Hines, "The Long-Run Cost Function of Water Production for Selected Wisconsin Communities", Land Economics, 45 (February, 1969) p. 133-140.

[c] Zvi Grilieches, "Cost Allocation in Railroad Regulation", Bell Journal of Economics and Management Science, 3 (Spring, 1972), p. 30. According to Griliches, a cross-section is preferred to a time-series, since the latter is affected strongly by short-run and irrelevant fluctuations.

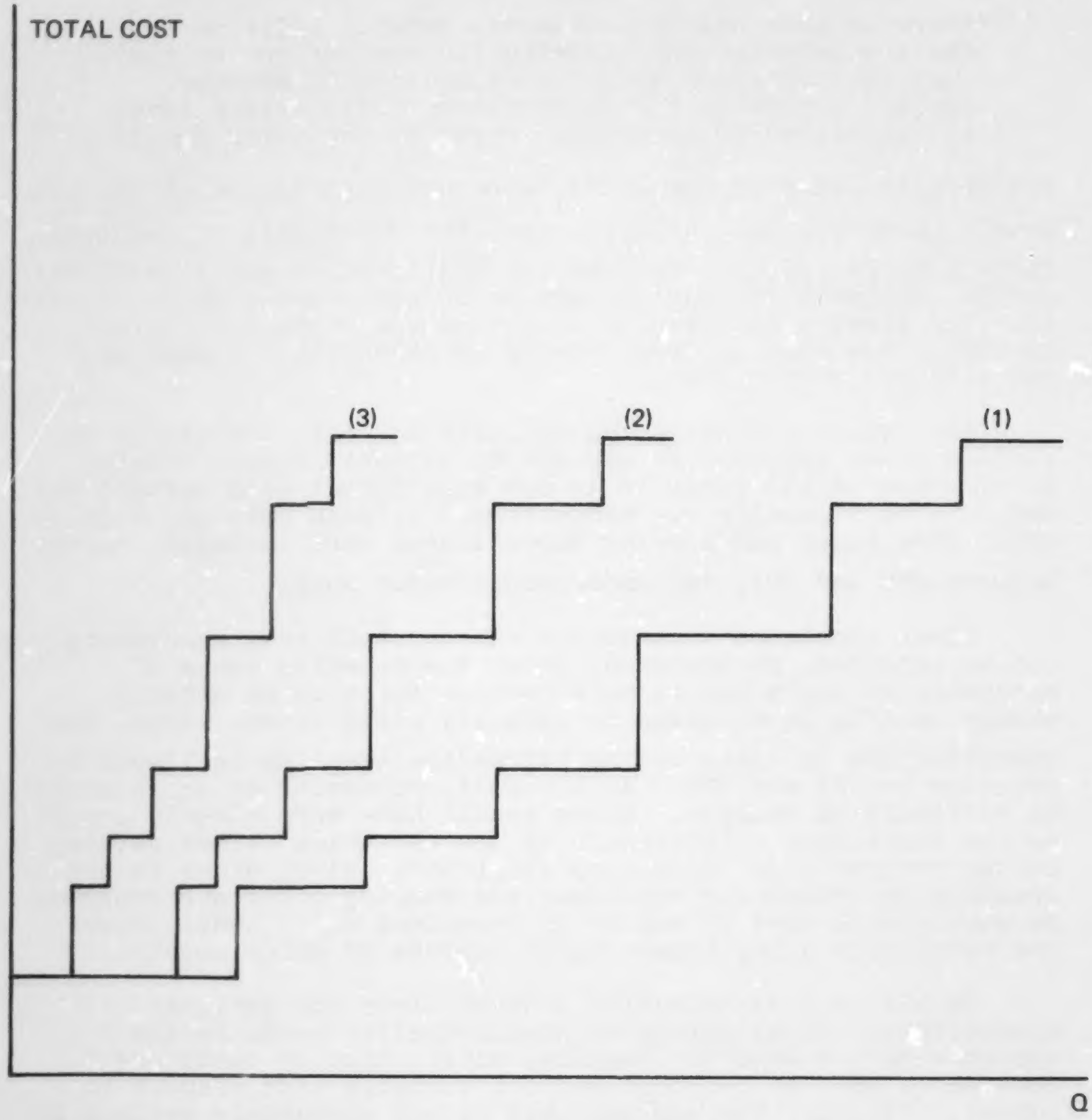

Figure 4. Step cost functions.

1957 price level; and API_2 = historical plant cost less power and pumping plant adjusted to the 1957 price level. Hines justifies this demarcation because:

> "there is more nearly continuous capital addition to the transmission and distribution part of the system than that of power and pumping equipment, and the capital change in the former is more directly related to the number of customers served by the water facility."[a]

The results obtained using API_1 were not significant at the .05 level. However, when API_2 is used, the hypothesis of constant costs must be rejected because the coefficients are significant at the .05 level for surface and underground water supply classes. The statistical results developed are presented in Table 1. For those two classes, the inverse relationships between cost and size are very evident.

The capacity utilization variable was only measurable for surface water supply. It appears to be more closely related to AFC than to AVC since it is not significant with respect to AVC. No relationship was demonstrated between cost and % CU or API_1, when power and pumping expenditures were included, except between AFC and API, for underground water supply.

Hines concludes that though the constant cost hypothesis can be rejected, no statement about the capacity range of economies of scale can be made because there is no orderly change in API_2 in relation to capacity utilization. Also, the specification by Hines of the regression equation is linear in relation to API and %CU. As a result, economies of scale would be difficult to analyze. Hines should have more clearly specified the functional relationship of the variables before setting up the reduced form regression equations. Also, Hines is not specific in explaining why power and pumping costs are dropped. He even admits that it may be an imperfect adjustment. Power and pumping is a legitimate major expense of water supply.

In his cost distribution between fixed and variable expenditures, Hines allocates administrative costs to the variable cost category. Usually, administrative costs are considered part of overhead and not variable with respect to output. Finally, the %CU variable is not adequately defined in the text of his analysis.

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[a] Hines, "The Long-Run Cost Function of Water Production for Selected Wisconsin Communities", p. 137.

TABLE 1.

SUMMARY OF SELECTED HINES' STATISTICAL COST REGRESSIONS.

A. Surface Water using API_2

(9 cases; 6 d.f.: 0.05 = 2.45)

i.) Average Fixed Cost (AFC)	= 132.5927	− 1.320(%CU)	− .000004373($\$API_2$)
	s.d.	(.30755)	(.000001428)
	t	(4.293)	(3.062)

ii.) Average Variable Cost (AVC)	=209.7173	− 1.4672(%CU)	−.00001092($\$API_2$)
	s.d.	(1.0125)	(.000004849)
	t	(1.450)	(2.252)

iii.) Average Total Cost (ATC)	= 342.3376	− 2.7880(%CU)	− .00001530($\$API_2$)
	s.d.	(1.0268)	(.00004917)
	t	(2.715)	(3.111)

B. Underground Water using API_2

(25 cases; 23 d.f.: 0.05 = 2.07)

i.) Average Fixed Cost (AFC)	= 77.9359	− .000004178 ($\$API_2$)
	s.d.	(.000001787)
	t	(2.337)

ii.) Average Variable Cost (AVC)	= 106.2546	− .000006971($\$API_2$)
	s.d.	(.0000033664)
	t	(2.071)

iii.) Average Total Cost	= 184.1822	− .00001114 ($\$API_2$)
	s.d.	(.0000048605)
	t	(2.294)

where ATC = AVC + AFC;
AFC = API_2/output; and
AVC = total operating costs less power and pumping operating costs/ output.

In general, Hines attempts to estimate the relationship between cost and %CU and between cost and API for surface and ground water supply. The statistical work is acceptable,[a] but the methodology employed leaves something to be desired.

A more detailed and precise attempt to estimate water supply costs was made by Ford and Warford.[b] Their work tries to explain unit costs in the water supply industry. On the basis of a cross-section sample for a given year, Ford and Warford want to estimate the long-run average total cost curve of the envelope category. Costs are defined as the sum of expenditures on sources of supply, transmission of water, and treatment of water.

The functional forms employed and used as regression equations are linear, quadratic, and exponential with a logarithmic or semi-logarithmic transformation.[c] The key explanatory variables chosen for estimation of the cost function are Q (daily supply in thousands of gallons), AREA (area in square miles), and Q/AERA. The results found are listed in Table 2.[d] Notice that equations 3, 6, 7, 8 and 9 provide the best results. In all five, the estimates of the coefficients are significant, they have the expected signs, the Von Neumann ratio is satisfactory, and the R^2s are highly significant.

These results can be obtained from the equations:

1). From equations 3, 6, 8, as Q/AREA increases, cost decreases; this signifies the existence of economies of scale in water supply.

2). From equation 7, holding Q constant, as AREA increases, costs rise, but at a decreasing rate.

3). Also, from equation 7, holding AREA constant as Q rises, average cost falls, but at a decreasing rate.

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[a] No R^2s were presented.

[b] J.L. Ford and J.J. Warford, "Cost Functions for the Water Industry", Journal of Industrial Economics, 18 (November, 1969), p. 53-63.

[c] The general forms are:

$C = a+bx$; $C = aQ^2 + bQ + d$;

$C = aQ^b$, or $C = \ln a + b \ln Q$, or

$\ln C = \ln a + b \ln Q$; and $C = ae^{b(Q)}$ or $\ln C = \ln a + b(Q)$.

[d] Ford and Warford, "Cost Functions for the Water Industry", p. 60.

TABLE 2. SUMMARY OF FORD-WARFORD STATISTICAL COST REGRESSIONS.

		R^2	d
1.	$C = 31.17* - .14Q* \times 10^{-3} + .36Q^2 \times 10^{-10}$	.018	2.12
2.	$C = 26.8* + .12\text{Area} - .13\text{Area}^2 \times 10^{-5}$	.024	2.10
3.	$C = 33.3* - .035\ (Q/\text{Area})* + .49\ (Q/\text{Area})^2 \times 10^{-5}$	.116*	2.09
4.	$\log C = 3.76* - .05* \log Q$	.020	2.07
5.	$\log C = 2.91* + .83 \log \text{Area}$	.094	1.62
6.	$\log C = 3.84* - .13 \log (Q/\text{Area})$	.219*	2.06
7.	$\log C = 3.78* + .133 \log \text{Area} - .124 \log Q*$	.214*	2.06
8.	$C = 46.58* - 4.23* \log (Q/\text{Area})$	.206	2.09
9.	$C = 53.37* + 3.92 \log \text{Area} - 4.82 \log Q$	.21	2.10
10.	$C = 52.8* - 2.63* \log Q$	.058	2.10
11.	$C = 19.75 + 1.99 \log \text{Area}*$	.045	1.41[a]
12.	$\log C = 3.3* + .14Q \times 10^{-7}$	.00	2.11
13.	$\log C = 3.23* + .00034\ \text{Area}*$	.057	2.14
14.	$\log C = 3.32* - .67\ (Q/\text{Area}) \times 10^{-4}$	.004	2.11
15.	$\log C = 3.23* + .00034\ \text{Area} - .43Q \times 10^{-7}$	.052	2.14
16.	$C = 29.49* + .11Q \times 10^{-5}$	.000	2.11
17.	$C = 27.31* + .084\ \text{Area}$	.028	1.55[a]
18.	$C = 29.8* + .0022\ (Q/\text{Area})$	.004	2.11

19.	$C = 27.3^* + .0086\ \text{Area} - .18Q \times 10^{-5}$	.024	2.11

Notes: d 15 Von Neumann ratio

* significant at 90% or better

a not significant at 5%

Thus, use of Q, Q/AREA, and AREA give some indication of the relation between area serviced and cost incurred. The cost of transmission is obscured because cost is examined in total and not disaggregated into major components. Therefore, the degree of existence of economies of scale as estimated may be misleading. Also, a cross-sectional study can indicate economies of scale at one point in time; but, there may be vast differences in the operating method or management of a utility in the sample which could bias the measure of return to scale.

In general, the article was methodologically correct and statistically significant in terms of results. But, the R^2 values were not very high, .219 for equation (6). Ford and Warford offer two conclusions on this subject:

> "either (a) we should break down costs into the production costs of the textbooks and seek to explain these by using our independent variables; or (b) the technological and natural differences that do exist between the various water undertakings in the industry-the unquantifiable variables-must be such as to rule out the existence of a so-called long-run cost curve for the industry; such technological differences between areas must swamp the independent variables we have used."[a]

Their latter conclusion may not be too important because the level of technology employed in the water supply industry is fairly equal at one point in time except where extreme age differences exist or where ground water vs. surface water differences exist which are not embodied in the model.

The next few articles reviewed here deal explicitly with the issue of economies of scale and total cost functions. The issue has been previously mentioned, but not directly discussed.

Returns to scale can be increasing, decreasing, or constant depending on whether the elasticity of cost to an explanatory variable as output is less than one, greater than one, or equal to one. Griliche[b] calls this the percent variable. It equals the ratio of marginal cost to average cost. McElroy,[c] in a comment on returns to scale, points out that one cannot make inferences about economies of scale at levels of output arbitrarily distant from the point estimated just on the basis of the sign of the slope of the average cost curve. McElroy adds that Bassett[a] criticized the use of point or arc elasticity to measure returns to scale because of either's inability to estimate correctly outside an ϵ - neighborhood. McElroy attempts to clear up the confusion by arguing that this is true of any approximating tangent line to a non-linear function:

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[a] Ibid., p. 61.

[b] Griliche, "Cost Allocation in Railroad Regulation", p. 27.

[c] F. McElroy, "Returns to Scale and Cost Curves: Comment," Southern Economic Journal 37 (October, 1972) p. 228.

> "It would seem, however, no more reasonable to conclude from it (Bassett's statement) that the slope in question provides no useful information about returns to scale, than it would be to argue that knowledge of the slope of the average cost curve at X provides no useful information about changes in average cost, on the grounds that it is an insufficient basis for determining whether average cost at X is higher or lower than average cost at outputs at arbitrarily large distances from X."[b]

Scarato,[c] in his article on urban water systems, briefly discusses economies of scale. Costs are divided into treatment and distribution, each consisting of capital and operatio-maintenance components. Capital costs for both treatment and distribution are theorized as exponentially related to capacity:

$$C = K\,(X)^{\alpha}$$

where C = total cost

X = capacity; and

α = constant, the cost elasticity with respect to capacity and a measure of economies of scale.

Scarato mentions the Orlob-Lindorf and Koenig studies on capital treatment expenditures as the foundation for his cost functions. In both articles, α was estimated as 0.67[d] thus exemplifying the existence of economies of scale. With respect to operation-maintenance expenses, the Orlob-Lindorf and Koenig studies are again given as basis for his analysis. Instead of capacity, though, average daily flow is used as the explanatory variable. Scarato argues that the operation-maintenance cost curve is a decreasing function over a capacity range becoming proportional to capacity and demonstrating economies of scale up to an output of 20 MGD.

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[a] Lowell Bassett, "Returns to Scale and Cost Curves", Southern Economic Journal, 34 (October, 1969), p. 189-190.

[b] McElroy, "Returns to Scale and Cost Curves: Comment", p. 228.

[c] R.F. Scarato, "Time Capacity Expansion of Urban Water Systems", Water Resources Research 5 (October, 1969), p. 929-36.

[d] See the Orlob-Lindorf and Koenig studies noted above.

Scarato only theorized the relationship of capacity to cost. In another article, F.T. Moore[a] reviewed some statistical and engineering analyses of economies of scale. He found that the statistical evidence in previous studies was incomplete.

Moore discusses some facts and relationships concerning economies of scale. The vehicle for analyzing the degree and existence of returns to scale is the envelope or long-run cost curve. Engineers have noticed that the cost of an item is frequently related to its surface area, while the capacity of the item increases in accordance with its volume. Moore refers to this as the .6 factor rule where the increase in cost is given by the increase in capacity raised to the .6 power. A form of this is:

$$C_2 = C_1(X_2/X_1)^{.6}$$

where C_1, C_2 = costs of two pieces of equipment; and

X_1, X_2 = their respective capacities.

The general expression is: $E = aC^b$

where E = capital expenditure;

C = capacity; and

a,b = parameters, $b < 1$ implies economies in capital costs.

Moore argues that returns to scale are best estimated if these three conditions hold for the industry in question: (1) the industry is not specified by a batch-operation, but a continuous process; (2) the industry is capital intensive; and (3) the industry produces a homogeneous product. Those conditions appear to fit the water supply industry in general.

Of 33 industries analyzed, the average value of b was found to equal .68, but the relationships were not significant (besides, a t-statistic on b was not presented). Therefore, the importance of the results remain unknown. Moore concludes that there are no scale factors which adequately test the hypothesis of constant returns. But, use of a curvilinear logarithm relation and more homogeneous data may improve the results.

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[a] F.T. Moore, "Economies of Scale: Some Statistical Evidence", Quarterly Journal of Economics, 73 (May, 1959), p. 232-45.

One other article examines the existence of economies of scale in relation to size of water utilities and communities. In this analysis, Andrews[a] attempts to investigate the total and per unit costs of providing water as these costs relate to the quantity of water produced and the size of the community in New Hampshire and New England. The general model specified has the form:

$$Y = aX_i^{b_i} \text{ or } \mathrm{Ln}Y = \ln a + b_i \ln X_i$$

Y = a log-identified dependent variable

where a = constant term;

X_i = a log-identified independent variable;

and b_i = elasticity or coefficient of log X_i

The data employed was obtained from the American Directory of Water Utilities (1968-69). It included information on annual total production of water, annual revenue, population served, and number of services. Andrews attempts to evaluate b, the cost elasticity and measure of returns to scale, using a log-log regression equation.

Total and average cost functions were estimated for two categories. One related cost to output and number of customer accounts; the other related cost to population and number of services. The statistical results are presented in Table 3. Andrews found, in equations 1-3, meager economies of size for New England and significant economies of size for partially or not metered utilities in New Hampshire. Metered utilities were not found to possess economies of size. Also, a 1% increase in water treated, holding the number of services fixed, resulted in a .1 to .3% cost increase as shown in equations 4-6. That implies that a very small cost increase occurs when water use per customer rises. The costly part for increased water production is the number of services or customers. Unit cost equations, equations 7-12, estimated by Andrews provided the same conclusions as the total cost equations.

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[a] R. Andrews, "Economies Associated with Size of Water Utilities and Communities Served in New Hampshire and New England," Water Resources Bulletin, 7 (October, 1971) p. 905-12.

TABLE 3. SUMMARY OF ANDREW'S STATISTICAL COST EQUATIONS.

Equation Number	Area+ Type	Constant Term	Elasticity: Total gallons produced, b_1, (standard error)	Elasticity Number of services, b2, (standard error)	R^2
1-6 Total Cost; 7-12 Ave. Cost					
(1)	New Hampshire Metered	5.4113	.9312(.0483)		.9184
(2)	Partially or not metered[1]	6.7012	.7774(.0480)		.7801
(3)	New England[1]	4.7122	.9166(.0088)		.9193
(4)	New Hampshire Metered	.7783	.3094(.1635)	.7227(.1842)	.9449
(5)	Partially or not metered[1]	.2805	.1261(.0864)	.9694(.1176)	.8861
(6)	New England[1]	.4875	.2283(.0257)	.8226(.0296)	.9354
(7)	New Hampshire Metered	.5510	-.0721(.0486)		.0623
(8)	Partially or not metered[1]	.6682	-.2217(.0480)		.2239
(9)	New England[1]	.4620	-.0766(.0086)		.0764
(10)	New Hampshire Metered	.0743	-.7147(.1624)	.7469(.1829)	.3825
(11)	Partially or not metered[1]	.0280	-.8726(.0864)	.9686(.1178)	.5972
(12)	New England[1]	.0584	-.7042(.0265)	.7501(.0306)	.4345
13 - 18 Total Cost			Elasticity: Population b_1(standard error)	Elasticity: Number of Services b_2(standard error)	
(13)	New Hampshire Metered	1.3446	1.0040(.0486)		.9283
(14)	Partially or not metered[1]	.6294	1.0989(.0533)		.8516
(15)	New England[1]	.7563	1.0661(.0084)		.9438
(16)	New Hampshire Metered	.3451		1.0605(.0472)	.9387
(17)	Partially or not metered[1]	.1804		1.1266(.0477)	.8827
(18)	New England[1]	.2549		1.0776(.0079)	.9517

[1] Excluding New Hampshire

Andrews drops gallons produced and adds population as shown in equations 13-18. The cost elasticity coefficients indicate that total cost increases about the same rate or faster than increases in population or number of services.

One problem, though, is the use of demand variables such as population and number of customer accounts to estimate cost. As a result, the structural form is estimated. Simultaneous equation analysis of demand and cost curves may allow the derivation of reduced forms and the estimation of simultaneously related parameters.

In general, the regressions demonstrate that if per capita water consumption would increase, holding the number of customers fixed, substantial economies of scale would be achieved.[a] Economies associated with community size were not as great as those found within the utility. As the population rose, there was a tendency for the larger communities to use more water per capita per day. Andrews suggests that larger communities apparently produce more public services that require water and also service a larger commercial base than smaller communities. Of course, other demand factors as increased incomes can contribute to such a rise in water use.

This discussion on total costs has attempted to present the relevant analysis to date on statistical cost estimation and existence of economies of scale for water supply systems. Most studies estimated cost as a function of design capacity or average daily flow. Other analyses added different explanatory variables, as area, population, and number of customers. Relationships between cost and those variables give indications of the degree of economies of scale with respect to market area. Existing empirical studies do not adequately deal with this issue. That economies of scale are achieved in treatment and total cost is generally accepted. But, further analysis should attempt to delve into the demarcation between treatment and distribution costs in relation to economies of scale.

Transmission Costs

The cost of water transmission consists of capital expenditures for pipeline, pumping stations, and storage facilities; and operation-maintenance expenses of which energy cost is a major element. Before reviewing the transmission cost studies, a short description of engineering hydraulic factors involved in water transmission will be presented.

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[a] J.F. Sleeman, "Economies of Water Supply," Scottish Journal of Political Economy, II (1955) p. 231-45. Sleeman found a similar relation in London, p. 241.

PHYSICAL FACTORS AFFECTING COSTS

Total dynamic head is the major element involved in water transmission engineering. It consists of three major elements: static head, velocity head, and friction head. The importance of total dynamic head rests upon the fact that power or energy consumption per unit of water is directly related to the degree of head existing in the system. Head can be defined as the pressure in pounds per square inch or as the number of feet of liquid which would exert an equal pressure on the horizontal surface at the bottom of a pipe. The height of the column of liquid producing the pressure is known as the head on the surface.

The height of a column of liquid is often termed the static head on the inlet or outlet of a pipe. It is the difference in elevation and is expressed as a certain number of feet. Total static head equals the vertical difference, in feet, between the supply level and the discharge level.

Velocity head refers to the kinetic energy possessed as the liquid moves through a pipe at any velocity. It is the distance through which the liquid must fall to acquire a given velocity and is found from[a] $hv = V^2/2g$ where

hv = velocity head, feet of liquid;
V = liquid velocity, feet per second; and
g = accleration due to gravity, 32.2 ft. per sec.^{2}

Friction head is also measured in feet. It is the equivalent head required to overcome the resistance of the pipe, valves, and fittings in the pumping system. Friction head is related to the liquid flow rate, pipe size, type of pipe, viscosity of fluid, and interior condition of the pipe. Friction head loss varies roughly with the square of the flow for a turbulent system and directly for laminar systems.[b] Once the particular

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[a] Tyler, Hicks, P.E. and T.W. Edwards, P.E., Pump Application Engineering (London: McGraw-Hill, 1971), Chapter 4.

[b] Ibid, p. 132. "The flow of a liquid is said to be laminar or turbulent, depending on the liquid velocity, pipe diameter, liquid viscosity, and density. For any given liquid and pipe, these four factors are expressed in terms of a dimensionless number called the Reynolds number, R." The following ranges apply: $R < 2000$, flow is laminar
$2000 < R < 4000$, flow is assumed turbulent, but could be laminar; and $R > 4000$, flow is turbulent.

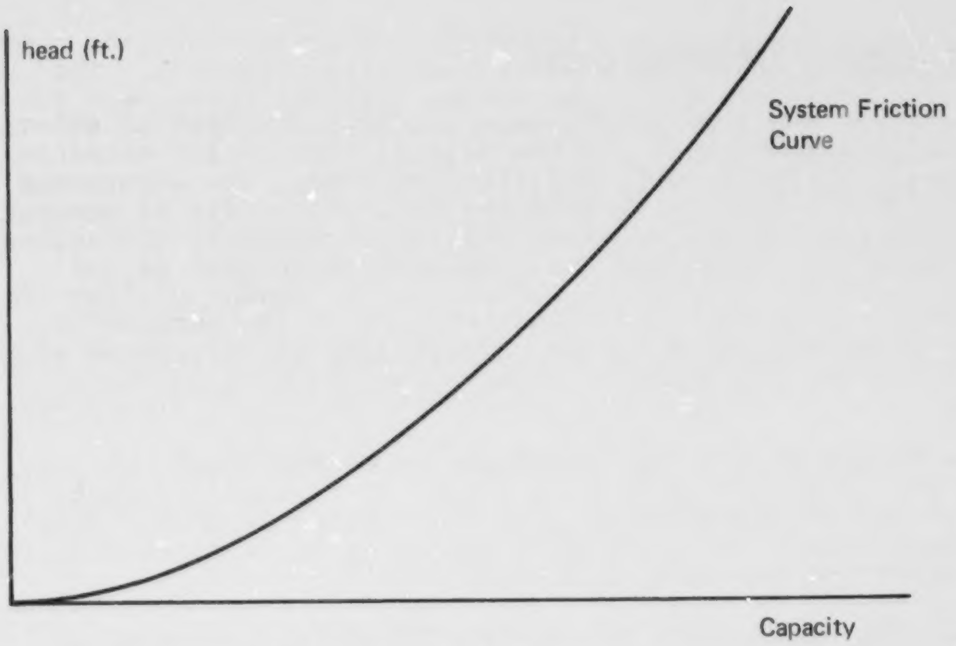

Figure 5. System friction curve.

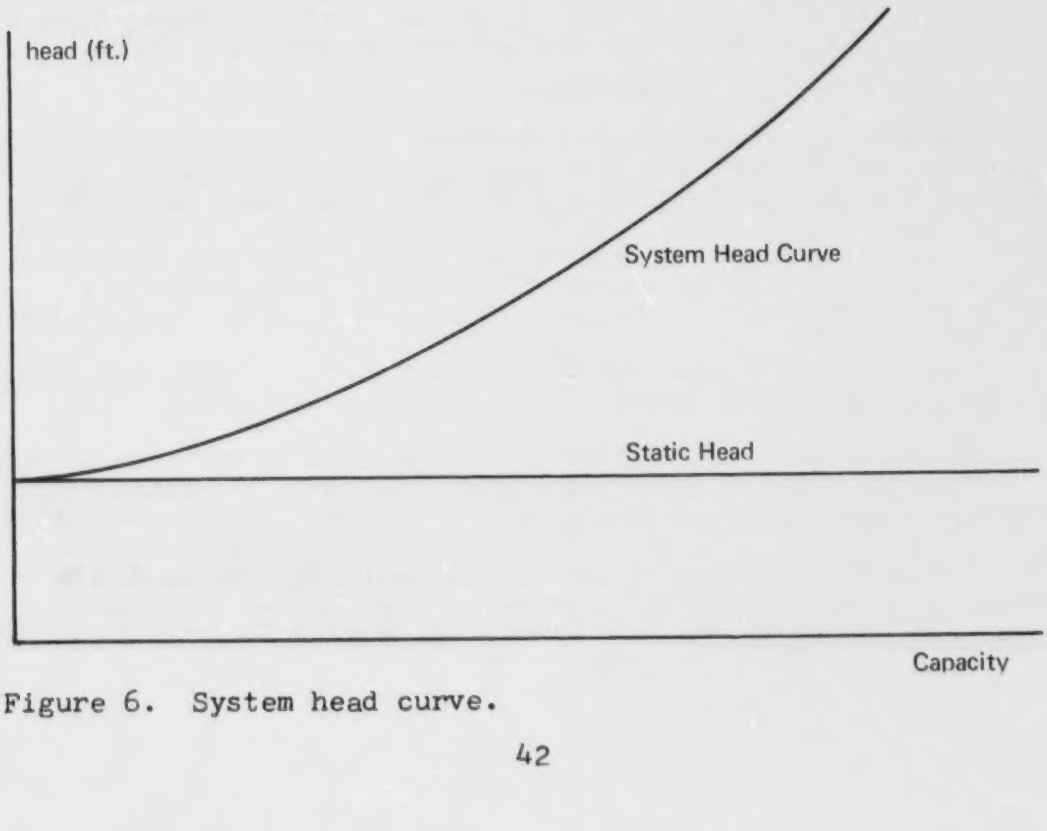

Figure 6. System head curve.

friction characteristics are determined, a system friction curve can be derived which plots head vs. capacity, Figure 5. The combination of static head, the system friction curve, and any pressure differences creates a system head curve, Figure 6. The system head curve can be used for examination of design characteristics in the transmission works. One issue that has received a lot of attention in the literature is the measurement of head loss and the key variables associated with it. Many approaches to the head loss measurement problem have been offered.[a]

Hicks and Edwards discuss one method in their book on pump application: $h = fLV^2/2gD$ or the Darcy-Weisbach formula where

h = friction head loss, feet of liquid pumped;

f = a friction factor

V = average velocity in pipe, feet per second;

D = internal diameter of pipe, feet; and

g = 32.17 feet per second squared

L = length of pipe in feet.

This is an engineering relationship. Given D, L, V, and a calculated f, h (friction head loss) can be determined. Suess[b] presents the same equation, but substitutes for V. Since, $Q = (\pi/4)D^2V$, where Q = quantity or flow capacity; $V^2 = (16Q^2/\pi^2D^4)$. Therefore, $h = f(16L/2g\pi^2D^5)Q^2$. Letting $K = f\,(16L/2g\pi^2D^5)$, $h = KQ^2$. This derivation is useful for simplifying the analysis. Many articles use a variation of this.

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[a] The studies of this issue are voluminous. A few relevant approaches are presented.

[b] Michael J. Suess, "Adoption of Equations for Analysis of Hydraulic Flow Systems by General Purpose Analog Computers", Water and Sewage Works, 114 (1967), p. R-41.

McPherson and Prasad[a] set up a functional relationship similar in nature to Suess: $\Sigma h = Qd^m = \varphi(Qp/Qd)^n$ where

h = head loss, feet;

Q_d = demand rate;

Q_p = pumping rate;

$Q_s = Q_p - Q_d$, the storage rate; and φ, m, n = constants.

The author developed this framework to define generalized network characteristics under proportional loading conditions. φ and n are determined by the data for a given m value. A simulation technique was used to estimate the optimal network conditions.

In another article, Singh[b] calculates head loss with: $Ho = 984.8\ f\ Vo^2/D \times 1.05$ where

Ho = head, feet of water;

f = Darcy-Weisbach friction factor;

Vo = average velocity of flow in the pipeline, feet per second;

D = inside diameter of pipeline, inches; and

1.05 = factor allowing for losses in the valves, bends, etc., in the pipeline.

This is a variation of the Darcy-Weisbach formula above. Singh computes f by using the Colebrook-White equation:

$$1/\sqrt{f} = -2\log_{10} (\epsilon/D)/3.7 + 2.51/Nr\sqrt{f}$$

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[a] M.B. McPherson and R. Prasad, "Power Consumption for Equalizing Storage Operating Options," Journal of the American Water Works Association, 58 (January, 1966), p. 67-90. See also: M.B. McPherson and M. Heidari, "Power Consumption with Elevated Storage compared to Direct and Booster Pumping", Journal of the American Water Works Association, 58 (December, 1966) p. 1585-94, and M.B. McPherson and R. Brasod, A Study of Distribution System Equalizing Storage Hydraulics (Urbana: The Department of Civil Engineering, University of Illinois, 1965).

[b] Krishan Singh, "Economic Design of Central Water Supply Systems for Medium Sized Towers", Water Resources Bulletin, 7 (February, 1971), p. 84.

where ε = the pipe roughness height, 0.005 inch for the useful life of 50 years of a cement-lined pipe; and

Nr = the Reynolds number.

The Colebrook-White equation is extremely complex. Solution requires computer analysis, or trial-by-error because of the logarithm term which hampers its degree of adaptability and use by water supply utilities.

An alternative to the Darcy-Weisbach type of head-loss equation is the Hazen-Williams formulation. In its original form, it is written: $V = .0001^{-.04}\,CR^{0.63}\,S^{.54}$, where V = average velocity in feet per second;

R = hydraulic radius of the pipe, feet;

S = L/H, a pure number in feet per foot;

L = length of pipe, feet;

H = headloss in pipe line, feet; and

C = a roughness coefficient.

Since $S = L/H$, $R = D/4$, and $V = Q/\frac{\pi}{4}D^2$ where D is the internal diameter of pipe in feet, and Q is capacity; the equation can be written as: $\frac{Q}{\frac{\pi}{4}D^2} = .0001^{-.04}\,C(\frac{D}{4})^{0.63}\,(\frac{L}{H})^{.54}$ or

$$Q/(\pi D^2/4) = .0001^{-.04}\,C(D/4)^{.63}\,(L/H)^{.54}$$

$$H = 4.72688\,C^{-1.8518}\,L/D^{4.870}\,Q^{1.8518}$$

Letting $K = 4.72688\,C^{-1.8518}\,L/D^{4.870}$, $H = KQ^{1.8518}$. That is a more simple expression as altered by Suess.[a] A variation of the Hazen-Williams equation was employed by Karmeli, Gadish, and Meyers[b] in their article on cost minimization of water distribution networks using linear programming. Their formulation is:

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[a] Suess, "Adoption of Equations for Analysis of Hydraulic Flow Systems by General Purpose Analog Computers", p. R-43.

[b] David Karmeli, Y. Gadish, and S. Meyers, "Design of Optimal Water Distribution Networks", Journal of the Pipeline Division, Proceedings of the A.S.C.E. 94 (PL1), (October, 1968), p. 1-10.

$$J = 1.13 \times 10^{12} (Q/C)^{1.852} D^{-4.87}$$

where

J = friction loss in meters per kilometer, in %;

Q = discharge, cubic meters per hour;

D = pipe diameter, millimeters; and

C = a friction coefficient.

Two differences stand out. First, the Hazen-Williams equation was converted to the metric system, and second, the length of pipe term, L, was apparently dropped. Derivation of the Karmeli, Gadish, and Meyers formulation was not presented in the article. But, J could be considered as H/L where H is headloss in meters and L is kilometers of pipe. Reasons for the change were not apparent.

There are two other interesting formulations to the problem of headloss measurement. One is by Rishel; the other is by Hey.

Rishel[a] examines headloss by using a system head curve, Figure 7 as calculated for each part of the system. At Qo, there is no flow. Q_2, $H = S + F$. Q_1 represents any intermediate flow that might occur in the system. Rishel postulates this relationship for those intermediate flows: $H = S + F (Q_1/Q_2)^2$. Obviously, if $Q_1 = Q_2$, the equation reverts to $H = S + F$. Rishel's formulation, though, is dependent on the knowledge of the system head curve and the nature of F. $H = S + F$ appears to ignore the problem. The theoretical derivation is similar in concept to the McPherson-Prasad model, but is much more simplistic. Actual computation of the system head curve and the friction element requires a great deal of information, the complexity of which is not examined in Rishel's article. Rishel does include the static head which none of the previous models included.

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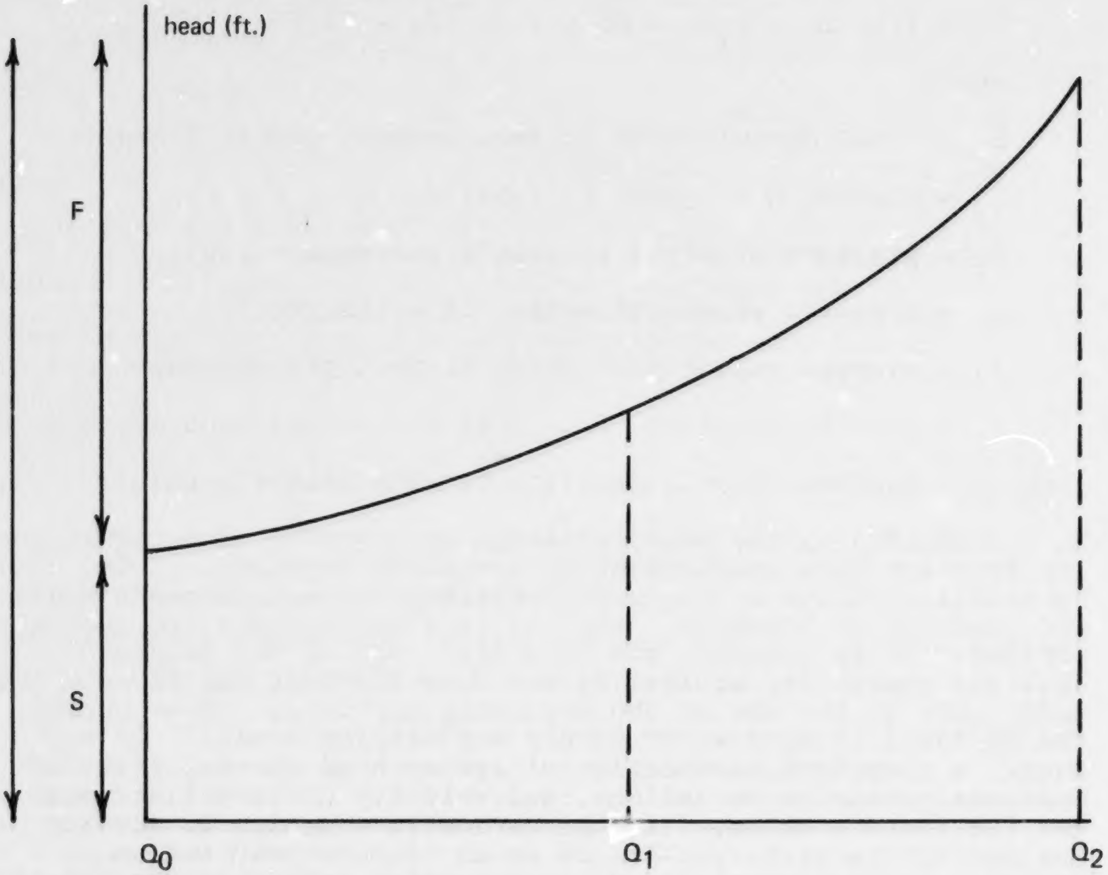
[a] James B. Rishel, P.E., "Packaged Pumping Stations for Suburban Water Distributions," Water and Sewage Works, 121 (1974) p. R-131-134.



Q = quantity of water pumped.
H = total head required of pump station.
S = static head of system.
F = friction head of system piping, valves, and fittings.
$H = S + (Q_1 / Q_2)^2$.

Figure 7. Head loss for a system head curve.

The other formulation os headloss measurement is the Bernoulli equation as presented by Hey.[a] It is the most complete, because it includes not only static and friction heads, but also velocity and pressure differences. Hey expresses it as:

$$E_p = Z_i - Z_o + P_i/\gamma - Po/\gamma + Vi^2/2g - Vo^2/2g + HL_{0-1}$$

where

E_p = total dynamic head in feet between points 0 and 1;

Z_i = elevation of point i, feet;

P_i = pressure at point i, pounds per square foot;

γ = specific weight of water, 62.4 lbs./ft.^{3};

V_i = average velocity at point i, feet per second;

g = gravity constant, 32.2 feet per second squared; and

HL_{0-1} = headloss due to friction between points 0 and 1.

HL is measured by the Darcy-Weisbach or Hazen-Williams equations for friction head measurement as described previously. The Bernoulli equation is the most comprehensive and complete model for analysis of headloss. All the relevant factors are incorporated. It is complex, but accurate. Use of the Hazen-Williams charts for estimating the C coefficient has reduced the difficulty in the use of the Bernoulli approach. Those charts can be found in many water supply engineering books.[b] In any event, a competent examination of system head curves, friction headloss, pressure variations, and velocity differentials must use the factors employed in the Bernoulli equation to develop the correct results, whether it is an engineer working on transmission optimization, or an economist analyzing the marginal cost differences of water transportation.

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[a] D. Hey, A Marginal Cost Basis for Metropolitan Water Supply Allocation and Operation. An unpublished Ph.D. dissertation, Northwestern University, 1974, p. IV-4.

See also: D. Hey and Robert Gemmell, Metropolitan Water Supply Allocation and Operation. (Urbana: Department of Civil Engineering, Water Resources Center, Northwestern University and University of Illinois, 1974).

[b] See: Gordon Fair and John Geyer, Elements of Water Supply and Waste-Water Disposal. (New York: John Wiley and Sons, 1958).

CAPITAL COST

With regard to water transmission cost, two components are important: capital and operation-maintenance cost. Capital costs of water transmission consist of the construction cost of pumping stations and pipelines. Storage facilities are not included because they are built for peak-load demands. Operation-maintenance costs include energy and repair costs incurred in the transmission of water.

Pipeline capital cost was estimated by Ackermann in a technical letter for the Illinois State Water Survey.[a] All cost figures were indexed to the 1964 cost level by means of the Handy-Whitman Index of Water Utility Construction Costs. Ackermann estimated an exponential relationship between construction cost and pipe diameter:

$$Cp = 2.16\ D^{1.2}$$

where

Cp = construction cost for a transmission line in dollars per mile;

D = pipe diameter, inches.

The results suggest diseconomies in per mile construction costs as the pipe diameter increases. Linaweaver and Clark[b] also estimated a similar relation between cost and diameter:

$$K = 1{,}890\ D^{1.29}$$

where

K = capital cost in dollars per mile; and

D = diameter in inches.

Again, the value of β implies diseconomies exist in the per mile construction costs of pipes as diameter increases.

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[a] William Ackermann, "Water Transmission Costs", Technical Letter 7, Illinois State Water Survey, 1967.

[b] F.P. Linaweaver and C. Clark, "Costs of Water Transmission", Journal of the American Water Works Association, 56 (December, 1964), p. 1552.

Both studies estimate cost per mile in relation to pipeline diameter and find diseconomies of scale.[a] Scarato[b], though, suggests that significant economies of scale exist between capital cost and pipeline capacity. He suggests a function of the type: $C = f\,[k\,(\text{capacity})^{\beta}]$ where C = total capital cost; k (capacity) = function measuring capacity; and β = parameter which measures the scale effect of capacity on total costs. Eliassen is mentioned by Scarato[c] as having measured a β as low as .56 which would imply economies of scale with respect to capacity, not diameter. Which is the proper approach, capacity or diameter, remains an unresolved issue. An alternative that might prove useful is to estimate the following relation:

$C = \alpha D^{\beta 1} L^{\beta 2}$ where

C = total construction costs;

D = diameter of pipe in inches;

L = length of pipeline in feet or miles;

and

$\beta 1$, $\beta 2$ = cost elasticity parameters

That could provide estimates of the degree of economies of scale with respect to diameter and length. As length increases, economies of scale should become prevalent.

Singh[d] presented a complicated approach to pump station cost estimation in his article on water supply systems. The capacity installed is assumed related to the headloss in the system. If head = 300 feet, then the capital cost of a pumping station is:

$$Cp = 17{,}000 + 135\,(P_{300})^{1.01}$$

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[a] Scarato, "Time Capacity Expansion of Urban Water Systems", p. 933.

[b] Neither article provided R^2s or t-statistics.

[c] R. Eliassen, The Economics of Water in the Pulp and Paper Industry, Engineering Economic Planning Program, Department of Civil Engineering, Stanford, California, June, 1967.

[d] Singh, "Economic Design of Central Water Supply Systems for Medium Sized Towns", p. 81.

where

Cp = total cost of a pumping station; and

P_{300} = the installed horsepower necessary to boost the water pressure 300 feet.

Singh does not present any regression statistics on the coefficients, on R^2, or the derivation of his specific functional form. The value 1.01 is definitely ambiguous as a measure of economies of scale. Its relevance to the cost function is not explained. Also, a relationship between cost and capacity is not examined.

In general, there does not appear to be any conclusive evidence for the existence of returns to scale in water transmission capital costs. The articles presented here have investigated specific factors, but have not analyzed or discussed all the relevant variables that may be better associated with capital costs.

OPERATING COST

Operation-maintenance cost is the second component associated with transmission costs. The relation between cost and quantity supplied is similar to that theorized by Coase[a], where the slope of the cost curve depended on the amount consumed at each distance from the supply curve.

Singh[b] presented some theoretical relations between operation-maintenance cost and certain key variables. For pipeline operation, maintenance, and repair costs:

$C = 10D$

where

C = cost per mile; and

D = diameter in inches.

That is a simple linear relation which is not unrealistic. Pipeline breaks can occur anywhere on old or new pipe. A linear distribution of costs based on pipe diameter is a close approximation to the actual cost of maintaining transmission lines.

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[a] See Figure 4.

[b] Singh, "Economic Design of Central Water Supply Systems for Medium Sized Towns," p. 79-90.

Energy costs are shown to be a function of static and friction headloss:

$C = kQ_o \text{ (Pf Ho + Ps Hs)}$

where

C = cost of energy per mile;

k = a relation dependent on the cost per kilowatt-hour and pump efficiency;

Pf = ratio of actual and constant energy cost spent during the year for friction headloss;

Qo = average yearly demand in gallons per day;

Ho = total headloss per mile of pipeline for a constant Qo;

Ps = ratio of actual and constant energy cost spent during the year for static headloss;

and

Hs = static headloss per mile of pipeline.

Singh proceeded through a complex derivation to arrive at the cost function. The function, though, neglects minor variations in the friction factor because he uses Qo instead of a Q that may vary. This could be an important factor in a residential district with a high peak to average demand ratio.

Singh also sets up a cost relation for pump station operation, maintenance, and repair cost which is not presented here. It is based on the P_{300} variable noted above, but, Singh does not provide the derivation of this cost function.

In the end, Singh combines all the factors of unit conveyance cost into one equation:

$Cu = 27.38\ C/Q_o$

where

Cu = cents per thousand gallons per mile;

Qo = average yearly demand in gallons per day;

and

C = total annual cost of conveying Qo through a pipeline of D inches for a distance of one mile.

This suggests that as Qo increases, Cu decreases. That is an empirical question which has not been adequately analyzed by Singh. Also, use of Cu hides any relevant marginal cost consideration. Singh does provide a graphical analysis of Cu for selected values of Qo and pipe diameter. But, his equation is derived from a set of seven other equations which apparently are not empirically estimated. It appears that Singh lifted specific relationships from various articles to derive his cost functions. Those derivations are not adequately explained.

One final article on water transmission costs by Linaweaver and Clarin[a] provides a coherent derivation of water conveyance cost functions. It combines engineering and economic considerations into one equation.

Capital cost of pipe was set up as:

$CK = Kf/365 \times 10^3Q(.75)$

where

CK = unit capital cost in dollars per thousand gallons per mile;

f = the capital recovery factor, $i(1 + i)^n/(1 + i)^n - 1$;

K = capital cost in dollars per mile[b]

365×10^3Q = thousands of gallons per year with capacity Q in millions of gallons per day;

and

.75 = the load building factor, proportion of utilized capacity.

Operation and maintenance costs consisted of the costs of energy required for pumping plus an added 8 per cent of that cost for other operation and maintenance expenses. Unit energy costs are:

$C_e = (\Sigma S)P/E$

S consists of friction loss, S_f, and an average line slope, S_L. S_L is defined as

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[a] Linaweaver and Clark, "Costs of Water Transmission", p. 1549-1560.

[b] $K = 1800D^{1.29}$ was estimated as noted above.

> "the difference in elevation in feet between the water level in the intake and discharge basins divided by the length of line in thousands of feet."[a]

Since this is constant overtime, a fixed load building factor of .75 is used. Sf, though, in the Hazen-Williams expression, varies approximately as $Q^{1.85}$. A load building factor of .667 is incorporated for Sf on the assumption that the average flow, at a given point over the design life, will be 2/3 of capacity.

Substituting these factors for S in Ce, the following relation is derived:

$C_e = 1.66 \text{ X } 10^{-2} (.75SL + .667\ S_f)\ P/E$. Since, $S_f = 10^3 \text{ X } Q^{1.85}/(405 \text{ X } 10^{-6}CD^{2.63})^{1.85}$, where C is the Hazen-Williams coefficient and D is the pipe diameter in inches,

$$Ce = P(1.66 \text{ X } 10^{-2})\ [.75S_L + .667(10^3 \text{ X } Q^{1.85}/(405 \text{ X } 10^{-6}CD^{2.63})^{1.85}]/E$$

Therefore, C_T, total unit transmission cost in dollars per thousand gallons per mile is: $CK + 1.08\ C_e$. Rewritten:

$$C_T = Kf(274Q \text{ X } 10^3) + 1.35 \text{ X } 10^{-2}PS_L/E + 12PQ^{1.85}/E\ (405 \text{ X } 10^{-6}\ CD^{2.63})^{1.85}.$$

Linaweaver and Clark provided a specific derivation of a general expression relating the principal factors that influence transmission costs to the cost of transporting water. There are two points of interest. First, this equation does not include any consideration of pump station capital cost. And second, the headloss characteristics incorporated do not allow for changes in pressure or velocity as done in the Bernoulli equation. If only short distances are analyzed, the pressure and velocity differentials can probably be ignored.

Transmission costs consist of capital and operation-maintenance expenses. This discussion reviewed the existing literature on measures of headloss and the theoretical and empirical studies of transmission costs. The empirical analyses were not rigorous in nature and the theoretical analysis of Singh was overly complex and unclear. Linaweaver and Clark did provide a competent approach to water transmission costs, but appear to overlook pump station capital cost.

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[a] Linaweaver and Clark, "Costs of Water Transmission", p. 1553.

PEAK-LOAD CONSIDERATIONS

Peak-load costs are reflected in the cost of storage tanks, greater capacity pumping stations, and larger sized pipelines. The empirical studies that investigated the costs of water supply ignored peak-load cost considerations. Instead, they examined average flow cost relations. This is probably due to the paucity of data on peak-load characteristics. The articles that do examine peak-load conditions usually analyze the trade-off between cost of increased pump capacity vs. increased storage capacity. Schmid[a] points out that

> "to produce at a greater pumping rate than the peak-day average may necessitate larger transmission and distribution mains and greater investment in booster stations and controls for limited use over the year. To produce at a lesser pumping rate than the peak-day average, on the other hand, requires costly additional storage."

Those considerations are important for future cost studies of water transmission systems. It is felt that more competent analysis is necessary in this field.

SUMMARY

This literature review has attempted to provide a background on certain key issues and factors involved in a water supply cost analysis. The two major areas studied were: methods of cost allocation and water supply cost.

The proper allocation of costs is the important issue in the first area. Many methods have been used to distribute costs, two of which are most frequently used by public utilities. They are the commodity-demand method and base extra-capacity method. Most discussion has centered upon the allocation of peak-load capacity costs to system users. Some authors promoted a distribution of costs based on a noncoincidental demand method. As a result, capacity costs are allocated on the basis of demand characteristics which are the ratios of peak to average use for each customer class. Therefore, those consumers with a high ratio, but no consumption at the system peak, could be allocated a large portion of capacity costs. The proper viewpoint involves the knowledge of the difference between joint and common costs. Joint costs exist when the capacity of a water works is available for use during peak and off-peak periods. Common costs occur if different customer groups consume at the same time at, for example, the system peak. As a result, no rate discrimination among customer classes that consume at the system peak should be made.

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[a] George G. Schmid, "Peak Demand Storage", Journal of the American Water Works Association, 48 (April, 1956), p. 384. McPherson and Prasad also analyzed the issue of storage vs. pumping capacity, but do not provide cost relationships.

One other point concerns the relevant dimension in which to analyze cost. Most authors reviewed suggest that marginal cost is the best concept on which to base decisions. The problem, though, is proper classification and estimation of marginal costs of each component analyzed: customer, commodity or base, and capacity cost.

The section of cost analysis in water supply reviewed theoretical and empirical studies on treatment, total, and transmission cost. Most studies consisted of attempts to empirically relate key explanatory variables to average and total cost. Capacity and per unit utilization were two major variables analyzed.

Attempts were made to estimate the degree of economies of scale in water treatment and the total cost of water supply. The results may be valid, but few studies supplied the regression statistics necessary to determine the significance of the estimated parameters. Also, it is difficult to estimate economies of scale for total cost of water supply. Because of the inherent physical andoperational differences between a treatment plant and a transmission system, separate estimation of the components would provide better knowledge of the degree of economies of scale. Combined analysis obscures information valuable for plant investments and expansion decisions.

Transmission cost empirical studies were not rigorous in relating key explanatory variables. Also, theoretical derivations and cost function specifications were inadequate. The engineering literature is extremely explicit and significant, but the economic application of engineering relationship needs further analysis.

Future research in this field should concentrate upon identification and estimation of peak-load costs and the marginal costs of each water supply component. Treatment cost has received much of attention, but transmission cost considerations have been largely ignored. Extension of water mains to the fringes of existing service areas will depend on such analysis. Only through comprehensive study of the relevant marginal costs can sound decisions be determined.

SECTION IV

METHODOLOGIES

PART A: COST ESTIMATION METHODOLOGIES

In order to carry out the analysis of cost rate differentials, data is needed on rates, usage or consumption, and the costs of delivering any amount of water to specific locations in the CWW (Cincinnati Water Works) service area.

Water rates are published, and data on usage is obtainable from the account records at the CWW, but costs are another matter. Part A of this chapter details the specific methodologies employed to obtain the cost estimates. Part B extends the analysis of Part A to the CWW area specifically, and explains how the data was gathered and applied to the problem.

Components of Water Supply Costs

To facilitate the analysis, we divide the water supply system into two major elements: (a) acquisition and treatment (A&T), and (b) transmission and distribution (T&D). Both elements, of course, contain capital and operating cost components. Overhead costs in this analysis will be treated as a constant and fixed cost per customer account. A&T functions occur within the framework of a centralized plant, and T&D in effect from the transportation system (pipelines, pumping stations and storage facilities) for finished water, and as a consequence, a proper economic cost accounting requires separation of these functions.[a]

A&T capital expenditure is determined by the design capacity of the plant. In a given time period, capacity is fixed and the marginal capital cost of another unit of output is zero unless water demand already equals capacity. Once capacity is reached, the marginal cost of capital for another unit of output must be included in the cost of production.

However, an important distinction must be made between capital available for peak vs. off-peak periods. In large scale plants, such as a water works, the base or average winter load may represent a significant portion of capacity. Therefore, capital consumption (wear and tear on capital equipment) can result to a large degree from off-peak use and accordingly that capital cost must be allocated to the average winter demand load. This would not be as important for a system with a very low ratio of off-peak use to plant capacity.[a]

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[a] Jarie S. Dojani and Robert S. Gemmell, "Economic Guidelines for Public Utilities Planning", Journal of the Urban Planning and Development Division, (September, 1973), p. 171.

Operating costs of A&T are directly related to the quantity of treated water produced. The marginal cost of operating the plant is not equal to zero regardless of the utilization of capacity; but it may remain constant over large ranges of output for a selected plant scale. Operating costs per unit of output can vary depending upon the economies of operation existing in a given capacity plant.

The combination of capital and operating costs can be useful in examining the A&T cost of peak-load periods and the degree of existence of scale economies. Analysis of returns to scale and costs at the system peak facilitate improved cost allocation.

T&D capital expenditure is determined by the design capacity of pipelines, pumping stations, and storage facilities. Pipeline diameter can be used to relate capital costs to capacity, since the volume of water flow possible in a transmission or distribution main increases as diameter increases. Other factors such as age and interior condition of the pipe are more important in their effect on operating costs, not capital costs. They will be discussed later.

The capacity of a pumping station is measured by the volume of pumped water it can handle during a given time period. To increase capacity, a larger facility and greater capital expenditure is required. This same relationship holds for storage tanks, in that the capacity is dependent upon the total available volume. Storage is utilized mostly during peak-load periods.

The marginal capital cost of another unit of output is zero for pipelines and pumping stations up to the point of capacity. As mentioned before in the section on treatment plant capital cost, however, off-peak demand may be a significant factor in capital consumption. Therefore, a proportional amount of capital cost must be allocated to the off-peak load.

Storage tanks are used only when the pipelines and pumping stations have reached capacity. Therefore, the marginal cost of capital for storage tanks is zero until the system peak-load has been reached.[a] This refers to the point in time when the demand load for a selected service area or the total service area is greater than or equal to the combined capacity of the system-pipes, pumping stations, and storage.

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[a] Ralph Turvey, "Peak-Load Pricing," Journal of Political Economy, 79, (December, 1968), pp. 101-113.

Operating costs of T&D, though determined on one main variable--energy, are very complex. A major portion of operating expenditures can be attributed to power consumption at pumping stations. Transportation of water over rough terrain and large distances requires a great amount of energy. Other operating costs such as manpower and maintenance are incurred, but they are not as significant or as directly related to output as energy consumption.

The energy cost of pumping water depends upon the quantity of water supplied, the distance to a demand point, and the net altitude between the demand point and supply point. Other operating expenditures remain relatively fixed with respect to output.

The marginal cost of operation varies over three dimensions: quantity, distance, and altitude. Examination of that relationship is a major concern of this study.

Theoretical Considerations

Existing price policies can lead to cross or internal subsidizations for users in all of the service areas: Pricing inefficiency resulting from inability or refusal to charge consumers on a benefits received basis, may allow substantial intra-area variation in the difference between rates and costs among users. Average net subsidy refers to the difference existing between the price paid and the cost incurred in the supply and demand for water. Three types of user subsidization may occur because of the distribution of costs over the service area and between peak and off-peak periods.

The first is reflected in distance to the customer. A greater amount of energy is required to pump water a long distance, for example twenty to thirty miles, than to supply a customer near to the plant.[b] In a similar manner, this is applicable to the second factor: topography. Customers served at a higher altitude require larger amounts of energy than those at lower altitudes. The head, (feet), necessary to supply consumers at various altitudes and distances affects energy consumption at the pumping stations. The third factor involves time of consumption. The cost of water supply varies depending upon whether demand occurs during the off-peak load or the system peak-load. Current water pricing mechanisms do not usually take account of such cost variations.

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[a] It is assumed in this analysis that storage tanks are erected for peak demand periods. As a result, the total storage cost can be allocated to the peak period even though tanks may be utilized during an off-peak period.

[b] Unless, of course, the customer resides at a lower altitude than the plant. Gravity flow can then be utilized. Of course, T&D capital costs will be higher for the more distant customer.

Peak vs. Off-Peak

Both distance and topography factors exist during the peak and off-peak demand periods. Therefore, distinct cost functions will be developed for the two separate demand loads or periods. With respect to water supply, the off-peak demand is identified as average daily water consumption during the winter period. The assumption here is that for Cincinnati no sprinkling or other peak-demands occur on an average winter day,[a] such that off-peak demand could approach system capacity. Off-peak demand reflects the system's base load which consists of residential domestic demand and a normal commercial and industrial load.

Peak demand for any user, whether residential, commercial, or industrial, may occur at any moment. But, peak demand for the system usually exists at a specific time during the year. Peak system demand refers to that period of time in which the daily quantity demanded reaches a maximum for the year. This may happen more than once a year, but usually occurs during the late summer when most lawn springling takes place.[b] Average daily demand during the system peak period is the dimension used to examine peak costs. The reason for this is two fold. First, very little storage is required to meat a peak day or a peak hour, but the peak week (or weeks) usually will strain the capacity of most water supply systems. Secondly, data on consumption is gathered either quarterly or monthly. As a result, average daily demand during the peak period is employed as an approximation to that of the peak week, which is not unrealistic since the system peak may last for more than one week.

Cost Function: Off-Peak Period

Two types of cost equations will be considered: peak and off-peak.

Off-peak costs are related to the base load on the system or the average daily winter load only. Use of average daily annual load would overstate the magnitude of the off-peak load since peak use is included in the annual totals. The total cost of supplying the ith consumer in a water service zone[a] k, can be estimated for the user's average daily load by adding together the relevant cost elements of A&T and T&D.

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[a] An average winter day generally occurs between December 1 and March 31.

[b] Peak system demand usually occurs between June 1 and September 30.

Although A&T cost consists of operating and capital components, average operating costs for the off-peak period will be considered constant for any single customer for mainly the reason that no single customer is large enough to influence off-peak operating costs measurably and identifiably. Also, we shall treat AC for A&T as a constant.

For capital expenditure or cost allocation, there is the problem of properly allocating costs between peak and off-peak periods. The capital facilities, though designed for the maximum day, is available during off-peak periods. Since, capital costs per unit of capacity vary depending upon the scale of the plant, and there exist economies of scale, it is difficult to evaluate off-peak capital costs for A&T. Therefore, the capital cost of A&T will be indirectly estimated for a hypothetical or simulated off-peak capacity plant to provide an estimate of the allocation of capacity cost to off-peak users.[b] This estimation can be derived from equations developed in previous articles discussed in the literature review.

Once the total capital expenditure relevant for off-peak production is determined, the capital cost per unit of capacity may be allocated. This cost is also assumed constant per unit of acquired and treated water. Therefore, to allocate capacity costs, each consumer is treated identically and as a result is apportioned a fixed capacity cost per unit of output. This represents the proportion of capital expenditure or capacity required by the consumer to supply his off-peak demand.

The following definitions apply to the analysis presented below:

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[a] A water service zone is based upon the direction of water flow and the placement of plumbing stations.

[b] This cost refers to "historical cost". Historical cost is the actual expenditure for a capital item. Reproduction cost measures the value of a replacement capital item in the present period.

Let:

q_{ikr} is the quantity of water consumed by consumer i in area r of zone k;[b]

$TCOP_{ikr}$ is the total off-peak treatment cost to supply q_{ikr};

$\bar{Q}$ is the total quantity of metered water produced by the A&T processes, cubic feet;

KOP^{T} is the total capacity required for off-peak loads by the A&T processes, cubic feet/day;

TC^{OT} is the total operating cost for A&T;

$TCOP^{KT}$ is the total off-peak capital cost for A&T;

$AC^{OT} = TC^{OT}/\bar{Q}$, average operating cost per unit of output; and

$ACOP^{KT} = TCOP^{KT}/KOP^{T}$, average off-peak capital cost per unit of capacity

Therefore, the total cost of A&T during the off-peak period for consumer i in area r of zone k can be defined as:

$$TCOP^{T}_{ikr} = q_{ikr}\ (AC^{OT}) + q_{ikr}\ (ACOP^{KT}) \text{ or} \tag{4-1}$$

$$TCOP^{T}_{ikr} = q_{ikr}\ (AC^{OT} + ACOP^{KT}),$$

where $q_{ikr} \cdot (AC^{OT})$ represents total A&T operating cost allocated to consumer i in area r of zone k and $q_{ikr}\ (ACOP^{KT})$ represents the proportion of total A&T capital cost allocable to consumer i in zone k. Note that: $(q_{ikr}/KOP^{T})\ (TCOP^{KT}) \equiv$

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[b] A service zone can encompass a large amount of land. Therefore, each zone can be subdivided into a number of areas according to census tracts or other geographic division. Note also that q_{ikr} represents the quantity of water consumed by i. The equation developed below can be used to calculate the costs of supplying water to an individual customer regardless of customer class (residential, commercial, or industrial).

$q_{ikr}(ACOP^{KT})$ and $q_{ikr}/KOP^{T} \equiv$ the proportion of capacity required consumer i in area r of zone k.

T&D cost also consists of operating and capital cost components. Operating costs are composed of energy and maintenance of equipment expenses. Capital cost refers to the expenditures on pipelines and pumping stations.

Since a principal focus of this study is to study explicitly the spatial aspects of water supply costs, this requires a deeper and more detailed examination of the determinants of T&D costs. The operating cost of T&D is highly complex in nature since it varies with respect to distance, topography, and output. Maintenance cost is incurred on pipelines and pumping stations, and in this study are considered constant per foot of pipeline and per cubic foot of pump capacity, respectively. Therefore, the operating costs which are variable with output, refer only to the cost of energy consumption.

The cost per unit of energy is constant in relation to each consumer in the same service zone. The magnitude of the cost per unit of output depends upon the head[a] required to supply consumer i in zone k. This varies over distance and topography.

Mathematically, energy cost per cubic foot for each linear foot of pipe can be represented by the following expressions.

Let:

$TCOP_{ikr}^{OD}$ is the total T&D operating cost incurred in supplying q_{ikr} to consumer i in area r of zone k;

Qkr is the total metered water supplied to area r of zone k during the off-peak, cubic feet/time period;

P_k is the off-peak cost of energy per kilowatt hour, \$/kwh;

S_a is the static head per foot of pipe, (ft.-lbs./lb.)/ft.;

S_f is the friction head per foot of pipe, (ft.-lbs./lb.)/ft.;

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[a] Head refers to the amount of energy required to meet friction, gravity, velocity, and pressure demands.

S_p is the pressure and velocity head per foot of pipe, (ft.-lbs/lb.)/ft.;

E_k is the efficiency of the pumping station in zone k, %;

$ACOP_{ijkr}^{OD}$ is the cost per unit of water in zone k in area r for pipe size j per foot of pipe, ($/cu.ft.)/ft.;

D_{jkr} is the diameter of off-peak pipe size j in area r of zone k, inches;

K_{ikr} is the net altitude between the treatment plant or pumping station and consumer i in area r of zone k, ft.;

C is the friction coefficient, a measure of roughness of pipe;

g is the gravity constant, 32.2 feet per second squared;

L_{jkr} is the length of pipe of diameter size j in area r of zone k, feet;

PR_k is the pressure in zone k, lbs./inch^2;

ρ is the conversion factor, 2.31 ft./(lbs/inch^2);

c is the conversion factor used to convert [(ft.-lbs./lb.) x (1/ft.) x ($/kwh)] to [($/cu.ft.) x (1/ft.)];

V is the average velocity, feet per second.

The unit pumping cost of output for pipe size j in area r of zone k is:

$$ACOP_{ojkr}^{OD} = (P_k/E_k)\ (S_a + S_f + S_p)\ c.^{a} \tag{4-2}$$

Since the dimension of $ACOP_{ijkr}^{OD}$ is [($/cu.ft.) x (1/ft.)], while the dimension of $(P_k/E_k)(Sa + Sf + Sp)$ is [($/kwh) x (ft.-lbs./lbs.) x (1/ft.)], a conversion factor, c, is required to establish dimensional homogeneity. Two conversion are necessary:

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[a] This equation is used in the literature by Linaweaver and Clark, "Costs of Water Transmission," *Journal of the American Water Works Association*, 56 (December, 1964) pp. 1549-1560; and W.C. Ackermann, "Cost of Pumping Water" Technical Letter 9, *Illinois State Water Survey* (July, 1968).

(a) (kwh/ft.-lbs.) = 3.77×10^{-7}; and

(b) (lbs./cu.ft.) = 62.37

Therefore, $c = 3.77 \times 10^{-7} \times 62.37$

$= 2.351349 \times 10^{-5}$.

The head on a pipe consists of static, friction, pressure, and velocity elements. For purposes of cost allocation, the pressure, velocity, and friction coefficients per foot of pipe can be assumed constant. Thus, variations in cost over distance and topography can be identified through the relationship derived in equation (6) from the appendix to this chapter. This equation establishes the following function for a given pipe size:

$$S_a + S_f + S_p = Z_{ikr}/L_{jkr} + (PR_k \times \rho + (4.8256 \times 10^5 Q^2 kr)/ (\pi^2 g\ D^4\ jk_r))/L_{jkr} + (2.85125 \times 10^5)\ Q_{kr}^{1.8518} \times C^{-1.8518} \times D_{jkr}^{-4.87}.$$

The problem remains, though, to calculate the head required to serve customer i in area r of zone k through an assortment of j pipe sizes. Water must be transported through some of the r areas of a zone, and only a few of the k zones. Each area may contain any combination of j pipe sizes and lengths.

Also, P_k and E_k may vary from zone to zone. Since a zone is defined by the direction of water flow, the pumping station serving one zone may use energy differently than another pump station supplying a different zone. Thus, changes in P_k and E_k are important in the examination of cost variations.

Incorporation of all those factors can be mathematically represented.

Let:

η_{ik} = 1, if consumer i resides in zone k or water to consumer i travels through zone k;

= 0, otherwise;

δ_{ir} = 1, if consumer i resides in area r or water to consumer i travels through area r;

= 0, otherwise; and

Y_{ijr} is the length of pipe size j in area r, feet.

Therefore,

$$(4\text{-}3) \quad TCOP^{OD}_{ikr} = q_{ikr} \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \sum_{j=1}^{n} Y_{ijr} \Big[P_k/E_k \; c$$

$$\times (Z_{ikr}/L_{jr} + PR_k \times \rho/L_{jr}$$

$$+ (4.8256 \times 10^5 \; Q^2{kr})/(\pi^2 g \; D^4{jr} L{jr})$$

$$+ 2.85125 \times 10^5 \; Q_{kr}^{1.8518}/C^{1.8518} D_{jr}^{4.87}/Q_{kr} \Big]$$

The term in brackets signifies the unit cost of pumping Q_{kr} per foot of pipe size j in area r of zone k, $ACOP^{OD}_{ijkr}$. This multiplied by the length of the jth pipe size, Y_{ijr}, in zone r; and added over all pipe sizes to obtain the pumping cost per cubic foot of water in area r of zone k. Summation of that unit cost over all r areas generates total energy cost necessary per unit of output to supply consumer i in area r of zone k.

There are principally two components to T&D capital expenditures: pipelines and pump stations. Maintenance costs incurred on pipelines and pump stations can be incorporated into considerations of capital cost.

As in treatment expenditure, the issue of peak-load cost allocation appears. Pipelines are designed to handle the peak-load, but exist during the off-peak also. Therefore, an off-peak network will be developed on the basis of capacity necessary to serve the average daily winter load.[a] Per foot cost of pipe may be calculated by using the amount that the Cincinnati Water Works actually incurred on pipes of each separate diameter, that is, historical cost.[b]

Maintenance cost for T&D pipelines is assumed constant here per foot of pipe per unit of capacity for all diameters. The reasoning for this rests upon the fact that no relationship has yet been established between the cost of repair and selected size mains. As a result, T&D pipelines maintenance cost will be considered as a fixed cost.

---

[a] Fire flow is considered part of the off-peak load.

[b] Pipe cost is not related to flow capacity since flow capacity varies with the age and condition of the pipe, while depreciation cost per time period still continues.

The mathematical description of pipeline cost relationships appears similar to that for energy cost in general formulations.

Let:

$TCOP^{KD}_{ikr}$ be the total off-peak T&D pipeline capital and maintenance expenses in area r of zone k, (constant over all R areas and K zones for a given size j);

K^{D}_{j} be the flow capacity for pipeline of size j; and

φ be the average maintenance cost per foot of pipe.

Therefore,

$$(4\text{-}4) \qquad TCOP^{KD}_{ikr} = q_{ikr} \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \sum_{j=1}^{n} \gamma_{ijr} \left[(AC^{KD}_{ijr} + \varphi) / (K^{D}_{j}) \right].$$

The term in brackets represents the average capital and maintenance cost per foot of pipe size j, per unit of capacity of pipe size j, in area r of zone k. The per unit capacity cost is multiplied by the amount of water supplied to consumer i. The parameters η, δ, and γ are used in the same manner as in equation (4-3).

The capital and maintenance expenditures for pump stations depends upon the capacity installed to transport water through each zone. The design capacity of pump stations is determined on the basis of peak-load demand, though the capacity in service is available for off-peak as well as peak-loads. Therefore, an off-peak capacity pumping system must be developed to correctly identify the off-peak capital T&D costs for the average daily winter load just as in the case of treatment and pipeline capital expenditures.

Capital cost per unit of capacity and maintenance cost per unit of capacity are assumed fixed in relation to each customer in the same zone. The proportion of capacity allocated to a customer depends upon the amount of capacity required by his average daily winter load. This occurs for each zone through which water must be transported to reach consumer i in zone k.

A mathematical formulation of pumping station capital and maintenance cost must incorporate those considerations of capacity.

Let:

$TCOP^{KP}_{ikr}$ be the total off-peak capital expenditures for T&D pumping stations;

K_k^P be the capacity available for the off-peak pumping station in zone k;

$ACOP_{ikr}^{KP}$ be the $TCOP_{ikr}^{KP} / K_k^{KP}$, average capital cost per unit of capacity during the off-peak in zone k;

TC_{ikr}^{MP} be the total maintenance cost for the pumping station in zone k;

$W_k \equiv TC_{ikr}^{MP}/K_k^{KP}$, average maintenance cost per unit of off-peak pump station capacity in zone k; and

$TCOP_{ikr}^{P} \equiv TCOP_{ikr}^{KP} + TC_{ikr}^{MP}$, total cost of maintenance and off-peak capacity for pumping stations allocated to consumer i in zone k.

Therefore,

$$(4\text{-}5) \qquad TCOP_{ikr}^{P} = q_{ikr} \sum_{k=1}^{K} \eta_{ik} [ACOP_{ik}^{KP} + W_k].$$

The term in brackets contains the average capital and maintenance cost per unit of capacity in zone k. This expression is summed over each zone through which water must be transported to serve q_{ikr} to consumer i. η_{ik} is again used to delineate the pumping stations used to serve consumer i from all available pumping stations.

The remaining element comprising off-peak water supply costs is overhead. Revenue collection, billing, meter reading, accounting, and administration are items unrelated directly to output or capacity of the system. As such, they may be considered as fixed overhead necessary for proper management of a water works. This cost can be allocated to each customer account on an even basis since every account incurs overhead costs.[a] Let Δ represent the overhead cost per customer for the peak and off-peak periods.

Off-peak costs may be mathematically defined by combining all the elements discussed above.

Let:

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[a] There is a difference between monthly billed and quarterly billed accounts in that the monthly account requires three meter readings and billings per quarter. This difference is negligible for cost allocations presented here.

$TCOP_{ikr}$ be the total off-peak costs of supplying consumer i in area r of zone k.

Therefore, from (4-1), (4-3), (4-4), and (4-5),

$$(4\text{-}6) \quad TCOP_{ikr} = TCOP^{T}_{ikr} + TCOP^{OD}_{ikr} + TCOP^{KD}_{ikr} + TCOP^{P}_{ikr} + \Delta.$$

Upon substitution into (4-6) for the total cost variables, the following cost function for the off-peak is generated.

$$(4\text{-}7) \quad TCOP_{ikr} = q_{ikr}\,(AC^{OT} + ACOP^{KT}) + q_{ikr} \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir}$$

$$\sum_{j=1}^{n} \gamma_{ijr}\,(Pkc/E_k) \times (Z_{ikr}/L_{jr} + PR_k \times \rho/L_{jr}$$

$$+ (4.8256 \times 10^5\ Q^2\ kr)/(\pi^2 gD^4{}_{j_r} L_{jr})$$

$$+ (2.85125 \times 10^5 Q_{kr}^{1.8518})/(C^{1.8518} \times D_{jr}^{4.87}))/Q_{kr}$$

$$+ q_{ik} \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \sum_{j=1}^{n} \gamma i_{jr}$$

$$[(AC^{KD}_{ijkr} + \varphi)/(K^{D}_{j})] + q_{ik} \sum_{k=1}^{K} \eta_{ik}\,[ACOP^{KP}_{ik}$$

$$+ W_k] + \Delta.$$

Rewritten:

$$(4\text{-}8) \quad TCOP_{ikr} = q_{ikr}\,[AC^{OT} + ACOP^{KT} + \sum_{k=1}^{K} \eta_{ik}\,(ACOP^{KP} + W_k)$$

$$+ \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta\ ir \sum_{j=1}^{n} \gamma_{ijr}\,(AC^{KD}_{ijkr} + \varphi)/K^{D}_{j}$$

$$+ \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \sum_{j=1}^{n} \gamma_{ijr} \times [(P_k c/E_k)$$

$$(Z_{ikr}/L_{jr}$$

$$+ PR_k \times /L_{jr} + 4.8256 \times 10^5 Q^2_{kr}/\pi^2 gD^4{}_{jr} L_{jr}$$

$$+ 2.85125 \times 10^5 Q_{kr}^{1.8518}/C^{1.8518} D_{jr}^{4.87})]/Q_{kr} + \Delta.$$

$TCOP_{ikr}$ represents the cost incurred in supplying one customer account in area r of zone k during the off-peak period. It is important to note that this equation does incorporate all the identifiable elements involved in off-peak water supply. The next section will discuss the peak-load cost problem.

Cost Function: Peak-Period

Off-peak capital costs reflect the capacity necessary to supply the base load on the system or the average daily winter demand. Capital costs required to serve the peak-load are one component of incremental capacity expenditures existing in a water supply system. The other is the expenditures needed to enlarge the whole or part of a system. For the purposes of this study, these incremental costs can be measured by subtracting the required off-peak capacity from the system capacity available for peak use.

Capital costs are fixed per unit of peak capacity as for the off-peak. In general, the peak-load cost function framework is similar to that for the off-peak except for considerations on capacity and storage. Total cost is also broken into A&T and T&D components.

Given the peak capacity A&T operating and capital costs remain fixed for each customer as in the off-peak period. Peak-load capital costs for treatment and acquisition consist of the expenditures on marginal plant capacity constructed to handle the maximum day.

Let:

q_{ikr} be the quantity of water consumed by customer i in area r of zone k;

TCP^{T}_{ikr} be the total peak-load treatment cost to supply q_{ikr} to consumer i in area r of zone k;

AC^{OT} be the average operating cost per unit of output;

TCO^{KT} be the total capital cost for A&T, or total peak-load capital cost for A&T;

KP^{T} be the total A&T plant capacity or total peak-load capacity available for A&T; and

ACP^{KT} $= TCP^{KT}/KP^{T}$, average peak-load capital cost per unit of capacity.

Therefore,

(4-15)[a] $TCP^{T}_{ikr} = q_{ikr}\,(AC^{OT} + ACP^{KT})$, where $q_{ikr}\,(ACP^{KT})$ equals the proportion of total treatment peak-load capital cost allocable to consumer i in zone k and $q_{ikr}\,(ACP^{KT}) = (q_{ikr}/KP^{T})\;TCP^{KT}$

T&D cost contains operating and capital cost elements. Operating cost consists of energy consumed in pumpage of water into the service areas. The cost of energy may be formulated in the same fashion as in the section covering off-peak costs. The only change is reflected in the variable D_{jr}, diameter of the pipe. For the off-peak period, the pipe diameter is smaller reflecting lower capacity requirements to meet demand. For the peak demand, though, the pipeline diameter must be larger to handle a greater flow. This change in diameter affects the friction and velocity heads in the transmission system and therefore the cost per unit.

Let:

PP_{k} be the peak-price of power in zone k, \$/kwh;

TCP^{OD}_{ikr} be the total operating cost in T&D incurred in supplying consumer i in area r of zone k;

D_{jr} be the diameter of pipe j in area r for the peak-load period;

QP_{kr} be the total metered water supplied to area r of zone k during the peak-period, cu. ft./time period;

and ACP^{OC}_{ijkr} be the cost per unit of q_{ikr} in zone k in area r for pipe size j per foot of pipe during the peak-period, (\$/cu.ft.)/ft.

Therefore, from (6) in the appendix, total head loss per foot of pipe may be adjusted to:

$$S_{a} + S_{f} + S_{p} = Z_{ikr}/L_{jkr} + (PRk \times \rho + (4.8256 \times 10^{5} \times QP_{k}{}^{2}{}_{r})/(\pi^{2} g D^{4}{}_{jr}))/L_{jr} + 2.85125 \times 10^{5} \times QP^{1.8518}_{kr} \times C^{-1.8518} \times DP^{-4.87}_{jr}. \tag{4-9}$$

Combining the changes in (4-9) with equation (4-3) provides the peak-load total operating cost in supplying consumer i in area r of zone k.

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[a] Equation number advanced from later in text.

$$(4\text{-}10)\quad TCP^{OD}_{ikr} = q_{ikr} \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \sum_{j=1}^{n} \gamma_{ijr} [(PP_k/(E_k)$$

$$\times (Z_{ikr}/L_{jr} + PR_k \times \rho /Ljr + 4.8256 \times 10^5$$

$$\times (QP_{kr}{}^2/\pi^2 gD^4{}_{jr}L_{jr}) + 2.85125 \times 10^5$$

$$\times QP_{kr}{}^{1.8518}/C^{1.8518} \times D^{4.87}_{jr})]/QP_{kr}$$

Use of peak D_{jr} may lower energy cost per foot of pipe since peak D_{jr} is larger than the off-peak D_{jr} used because of greater load requirements. The total effect, though, depends upon the volume of metered water pumped as well as the pipe diameter.

T&D capital and maintenance cost for pipelines and pumping stations remains to be discussed. A large capacity exists for supplying customers during peak-load periods. Capital and maintenance cost per foot of pipe per unit of capacity for all consumers for a given pipe size. Also, capital and maintenance cost per foot of pipe size j per unit of capacity does not change between the peak and off-peak periods for a given pipe size, but the cost to consumer i varies. The reasoning behind this rests on the fact that the pipe sizes used to serve customer i changes, which affects the capacity available in the T&D system.

Let:

TCP^{KD}_{ikr}	be the total peak T&D pipeline capital and maintenance expense in area r of zone k;
AC^{KD}_{ijkr}	be the average capital cost per foot of pipe size j in area r of zone k (constant over all R areas and K zones for a given size);
φ	be the average maintenance cost per foot of pipe; and
KP^{D}_{j}	be the flow capacity of pipe size j for pipelines used during the peak-load.

Therefore, total pipeline cost to consumer i for the peak-load period may be mathematically represented by the following equation.

(4-11) $$TCP^{KD}_{ikr} = q_{ik} \sum_{r=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \sum_{j=1}^{n} \gamma_{ijr} [(AC^{KD}_{ijkr} + \varphi)/ KP^{D}_{j}].$$

This equation is very similar to (4-4) in the off-peak cost section. The only differences are in the pipe flow capacity variable, KP^{D}_{j}, and the values of AC^{KD}_{ijkr}. Since larger pipe sizes are used during the peak period, KP^{D}_{j} changes for a selected customer and AC^{KD}_{ijkr} correspondingly varies with the pipe diameter as KP^{D}_{j} changes. Peak-load capital and maintenance costs only reflect changes in pipe diameter and capacity since the capital and maintenance cost for a foot of pipe is the same regardless of whether that pipe size is used in the peak or off-peak periods.

Pumping station capital and maintenance cost for peak-load periods reflect the capacity necessary to serve greater demand rates. Capital and maintenance cost per unit of capacity is constant for each customer, but varies between peak and off-peak periods because different design capacities are required to meet the two types of demands. Capital facilities are constructed in relation to a specific capacity. The cost of capital per unit of capacity, therefore, depends upon the design volume of the plant and the degree of economies of scale existing in construction of capacity. As a result, capital cost per unit of plant capacity may vary between periods. Maintenance cost per unit of capacity is constant within a demand period, but can change between the off-peak period because capacity available for T&D is increased for the peak-load.

Let:

TCP^{P}_{ikr} be the total cost of maintenance and peak-load capacity for pumping station allocated to consumer i in zone k;

TCP^{KP}_{ikr} be the pumping station peak-load capital expenditures for T&D;

KP^{P}_{k} be the pumping station capacity available for the peak-load in zone k;

ACP^{KP}_{ikr} be the $TCP^{KP}_{ikr}/KP^{P}_{k}$, average capital cost per unit of capacity during the peak-load in zone k;

TC^{MP}_{ikr} be the total maintenance cost for the pumping station in zone k; and

WP_k be the TC^{MP}_{ikr}/KP^{KP}_k, average maintenance cost per unit of peak-load pump station capacity in zone k.

Therefore,

$$(4\text{-}12) \quad TCP^{P}_{ikr} = q_{ikr} \sum_{k=1}^{K} \eta_{ik} \, [ACP^{KP}_{ik} + WP_k].$$

This expression closely resembles that discussed in the section on off-peak costs, equation (4-5).

The remaining element in off-peak costs is overhead. This cost may be allocated to each account as similarly done for the off-peak cost. Thus, Δ again represents the overhead cost per customer.

A final element, not incorporated in the off-peak cost equation, is storage cost. At certain times, the demand rate may be greater than the peak-load capacity of pumping stations and pipelines. For those occasions, storage facilities are constructed to supply water and maintain pressure when the system is overloaded. Storage cost is primarily a peak-load cost allocable to peak-load users. Cost can be apportioned to consumer i according to the amount of water demanded by consumer i in relation to the total quantity of water supplied during the period to the area in which consumer i resides.

Let:

QP_{ki} be the quantity of metered water supplied to area r in zone k;

q_{ikr}/QP_{kr} be the proportion of water used by consumer i;

TC^{S}_{kr} be the total cost of storage to consumer i in area r of zone k; and

$AC^{S}_{kr} = TC^{S}_{kr}/QP_{kr}$, average cost of storage per unit of output supplied to area r of zone k.

Therefore,

$$(4\text{-}13) \quad TCP^{S}_{ikr} \equiv q_{ikr} \, (AC^{S}_{kr}).$$

The proportion q_{ikr}/QP_{kr} provides information about the relative demand-load consumer i places upon the system capacity available for serving zone r. Consequently, it is assumed that the total storage cost can be divided among users on that basis.

Combining all terms involved in peak-load costs, the following equation may be generated.

Let:

TCP_{ikr} be the total peak-load costs of supplying consumer i in area r of zone k.

Therefore, from (4-15), (4-17), (4-18), (4-19) and (4-20),

$$(4\text{-}14) \quad TCP_{ikr} = TCP^{T}_{ikr} + TCP^{OD}_{ikr} + TCP^{KD}_{ikr} + TCP^{P}_{ikr} + TCP^{S}_{ikr} + \Delta.$$

Upon substituting into (4-14) for each TCP variable, this cost function is generated.

$$\begin{aligned}(4\text{-}15) \quad TCP_{ikr} = {} & q_{ikr}\,[AC^{OT} + ACP^{KT}] + q_{ikr} \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \\ & \sum_{j=1}^{n} \gamma_{ijr} \text{ x } PPk\ c/E_{k}\,[Z_{ikr}/L_{jr} + PR_{k} \text{ x } \rho/L_{jr} \\ & + 4.8256 \text{ x } 10^{5} \text{ x } (QP^{2}_{kr}/\pi^{2} gD^{4}{}_{jr}L_{jr}) + 2.8515 \\ & \text{x } 10^{5} \text{ x } QP^{1.8518}_{kr}/C^{1.8518} \text{ x } D^{4.87}_{jr}]QP_{kr} + q_{ikr} \\ & \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \sum_{j=1}^{n} \gamma_{ijr}\,[(AC^{KD}_{ijkr} + \varphi)/KP^{D}_{j}] \\ & + q_{ikr} \sum_{k=1}^{K} \eta_{ik}\,[ACP^{KP}_{ik} + WP_{k}] + q_{ikr}\,[AC^{S}_{kr}] + \Delta.\end{aligned}$$

Combining terms:

$$\begin{aligned}(4\text{-}16) \quad TCP_{ikr} = {} & q_{ikr}\,[AC^{OT} + ACP^{KT} + \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \sum_{j=1}^{n} \gamma_{ijr} \\ & \text{x } PP_{k}c/E_{k}\,(Z_{ikr}/L_{jr} + PR_{k} \text{ x } \rho/L_{jr} + 4.8256 \\ & \text{x } 10^{5} \text{ x } (QP^{2}_{kr}/\pi^{2} gD^{4}{}_{jr}L_{jr}) + 2.85125 \\ & \text{x } 10^{5}\ QP^{1.8518}_{kr}/C^{1.8518} \text{ x } D^{4.87}_{jr})/QP_{kr} \\ & + \sum_{k=1}^{K} \eta_{ik} \sum_{r=1}^{R} \delta_{ir} \sum_{j=1}^{n} \gamma_{ijr}\,(AC^{KD}_{ijkr} + \varphi)/KP^{D}_{j}\end{aligned}$$

$$+ \sum_{k=1}^{K} \eta_{ik} \left(ACP_{ik}^{KP} + WP_k\right) + AC_{kr}^{S} \rbrack + \Delta.$$

Equations (4-8) and (4-16) provide a complex framework in which to estimate water supply costs for a given point. Both are highly complex in formulation and use, but, as such, that does not hiner the analysis. These two equations will be used to generate data points that relate cost of water to distance, altitude, and quantity supplied for two time periods; peak and off-peak. Once the data points have been collected, statistical analysis of the relationship among the variables will be performed.

PART B: EMPIRICAL METHODOLOGIES

This part is devoted to a description of the study area, statement of the principal hypotheses to be investigated, presentation of the statistical equations to be estimated, the estimation of scale economies in water supply in the study area, and the framework for analysis of cost-rate differentials.

The Study Area

The area studied consists solely of the service area of the CWW which is contained in Hamilton County, Ohio (see Figure 8). The CWW is a self-supporting public utility which has operated over one hundred years with the Ohio River as the sole source of supply. Its treatment plant is located in the southeastern corner of the County.[a]

Water is acquired from the Ohio River, and after treatment is transported to the ten service zones of the supply area (See Figures 9and 10). These zones are defined essentially on the basis of water flow and on the location of pump stations. Since the direction of water flow is a variable, the zone definitions are based on averages.

Empirical Framework

From the literature review (Section 3) it was concluded that virtually no empirical study has been performed on water supply T&D costs of a metropolitan water system. Much of this research has concentrated on the central plant functions of water supply (A&T) only, and has neglected the measurement of peak and off-peak costs. Furthermore, current water pricing or rate setting methods, especially commodity demand or base-extra capacity methods, neglect that inter-user relationships that exist as a result of cross-subsidizations which result from uniform or relatively uniform zonal or spatial charges.

To measure these impacts, it is useful to have fairly concise measures or representations of water supply costs especially in order to measure scale economies in T&D. To

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[a] Construction was completed and operation began of a new A&T plant in late 1976, supplied with ground water. The study period does not include the impact of this plant.

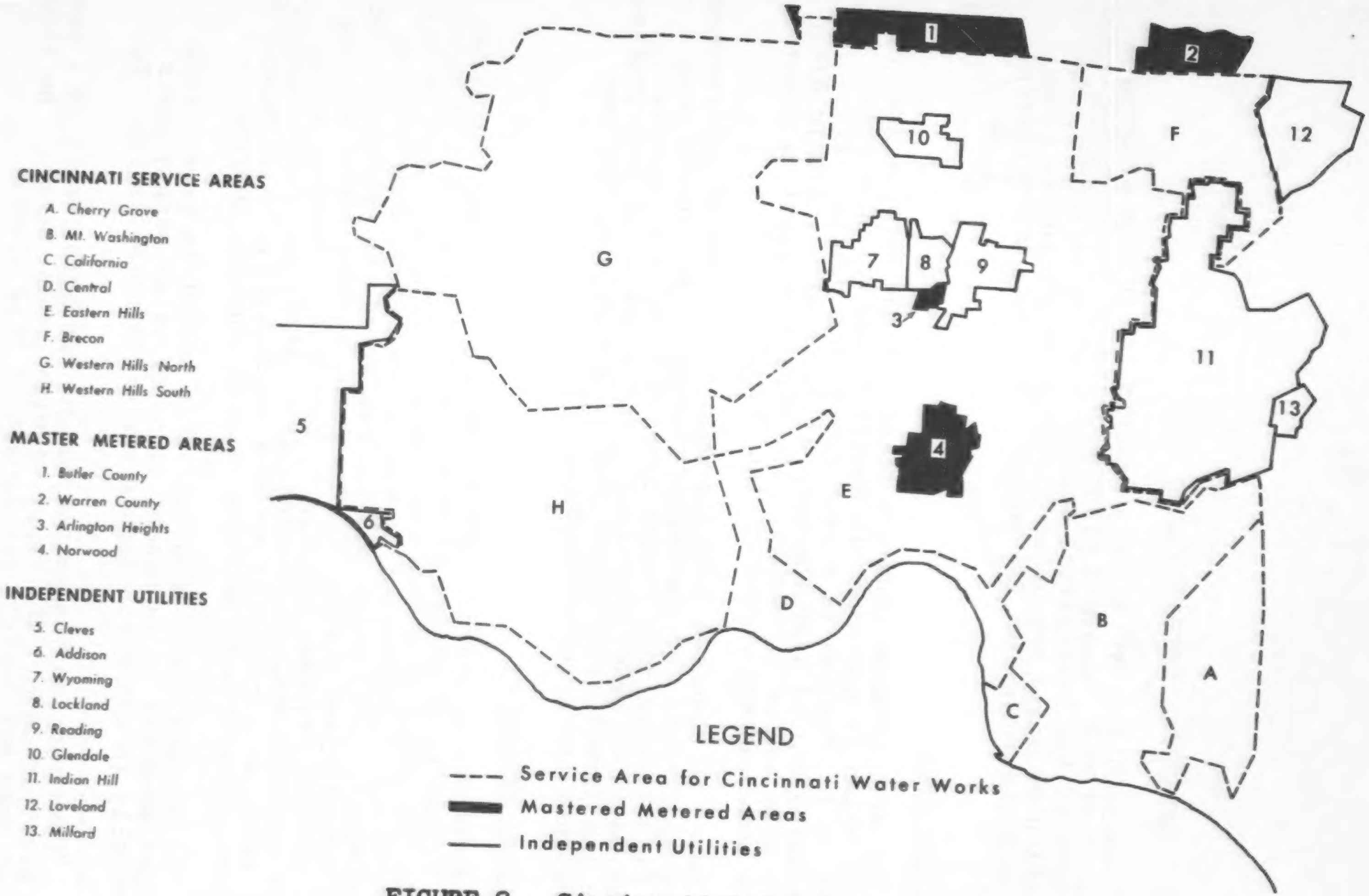
CINCINNATI SERVICE AREAS
A. Cherry Grove
B. Mt. Washington
C. California
D. Central
E. Eastern Hills
F. Brecon
G. Western Hills North
H. Western Hills South
MASTER METERED AREAS
1. Butler County
2. Warren County
3. Arlington Heights
4. Norwood
INDEPENDENT UTILITIES
5. Cleves
6. Addison
7. Wyoming
8. Lockland
9. Reading
10. Glendale
11. Indian Hill
12. Loveland
13. Milford
A
B
C
D
E
F
G
H
1
2
3
4
5
6
7
8
9
10
11
12
13
LEGEND
Service Area for Cincinnati Water Works
Mastered Metered Areas
Independent Utilities

FIGURE 8. Cincinnati Water Works service area.

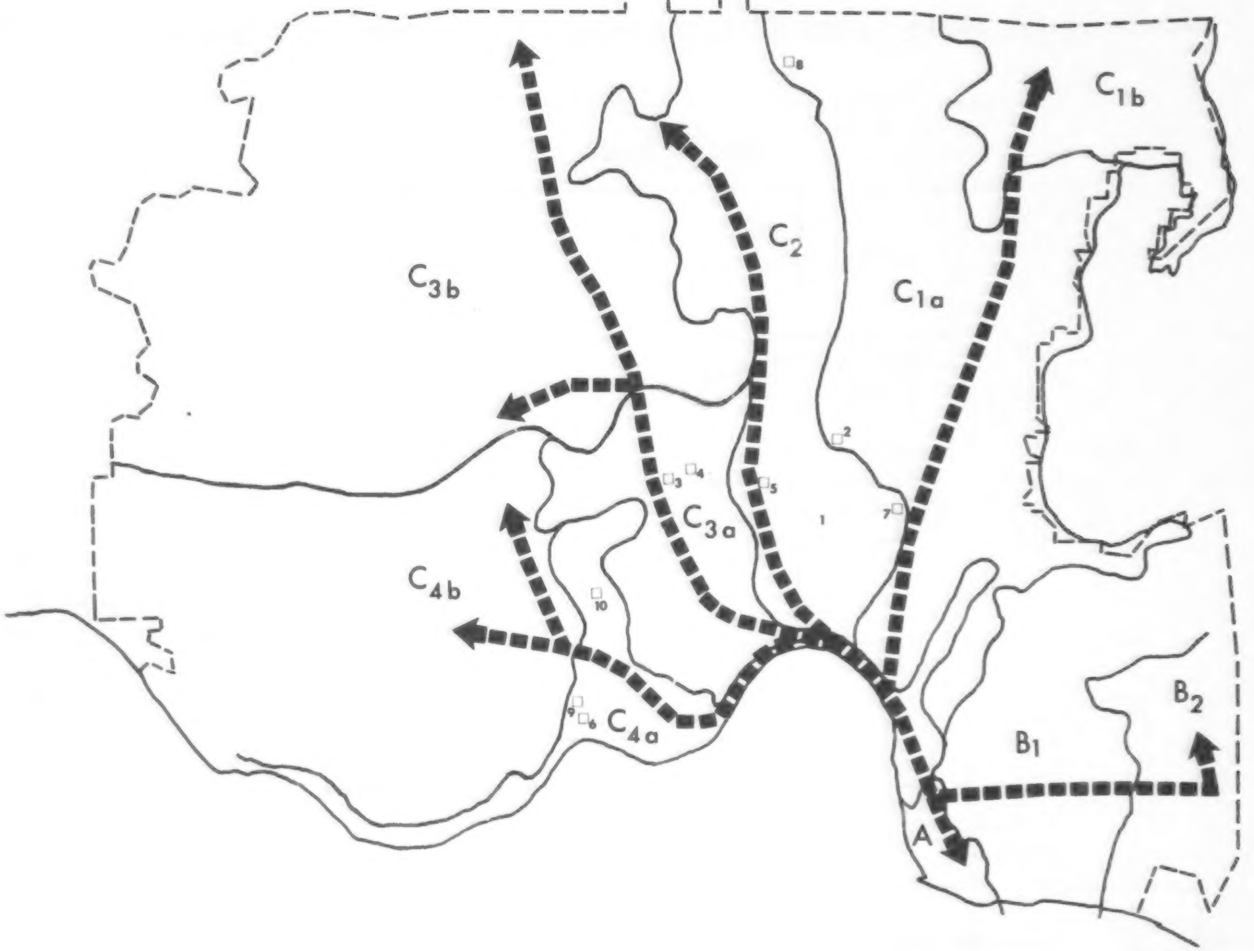
C_{1b}
C_2
C_{1a}
C_{3b}
C_{3a}
C_{4b}
C_{4a}
B_1
B_2
A
1
2
3
4
5
6
7
8
9
10

FIGURE 9. Service area and zones of the Cincinnati Water Works.

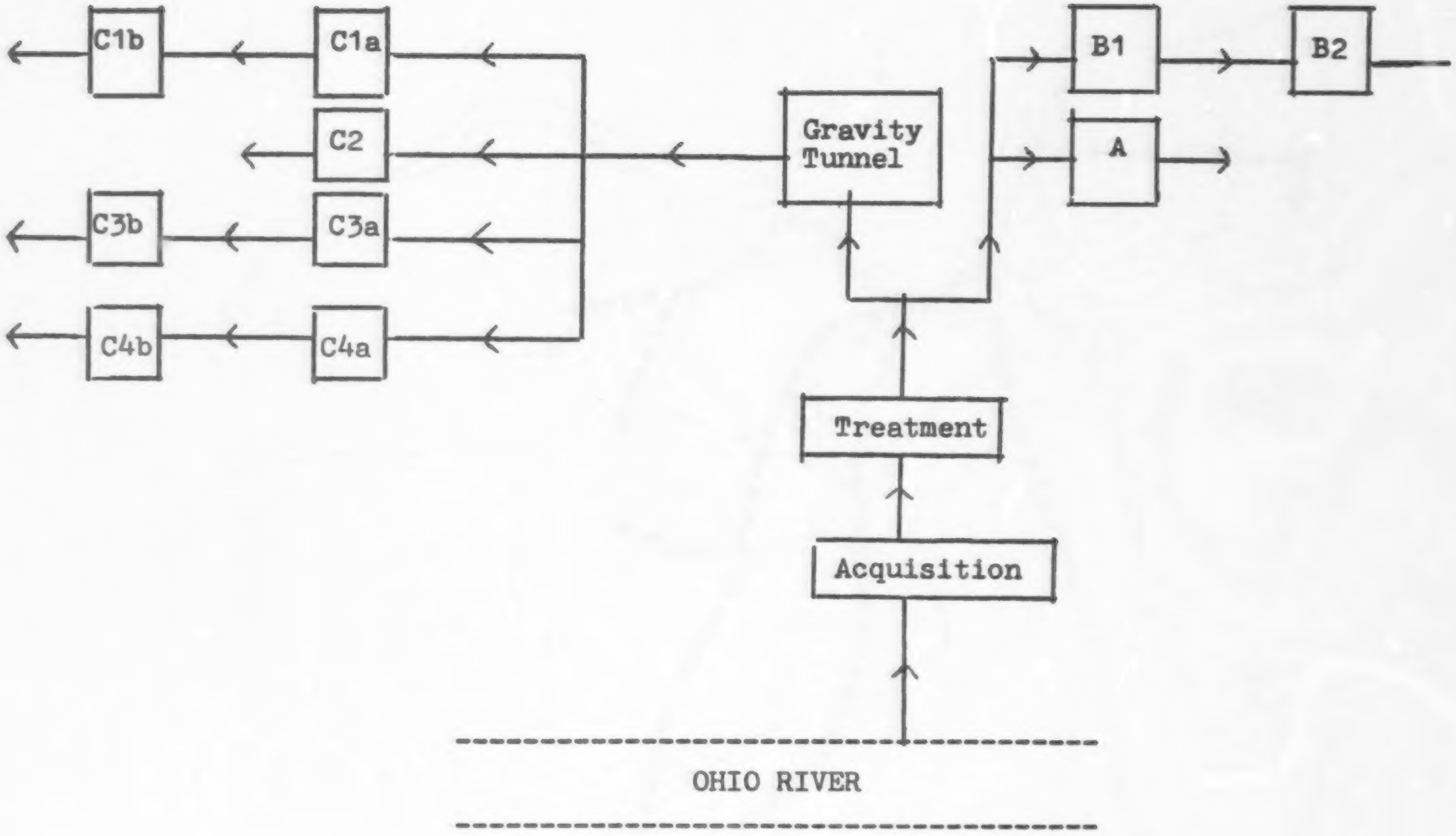
C1b
C1a
C2
C3b
C3a
C4b
C4a
Gravity Tunnel
B1
B2
A
Treatment
Acquisition
OHIO RIVER

FIGURE 10. Schematic diagram of Cincinnati Water Works system.

this end a number of statistical hypotheses were formulated and estimated.

Major Hypotheses: Cost Functions

There are alternative approaches to the estimation of cost functions. Two discussed by Johnston are: (a) functions estimated through the use of accounting and engineering records, and (b) through explanatory variables or determinants of cost variables.[a]

This research utilizes elements of both approaches. Water supply costs traditionally have been examined in the framework of quantity produced, capital invested, capacity available, and/or the proportion of capacity utilized. This may be represented by: $C = C(Q)$ in general or $C = aQ^b$ specifically where C = cost and Q = finish water produced. The data collected usually consist of a cross-sectional sample of utilities intended to provide information about the shape of the long-run cost curves (variable plant size). The interesting element in such studies is the fact that water supply utilities consist of two major components: A&T and T&D. Any measure of economies of scale using aggregate data overlooks information on the components of water supply in particular, the spatial aspects. Therefore, through a comprehensive study of one utility, as has been undertaken here, information on changes in T&D cost over the service area of the utility may be generated.

To examine these spatial aspects then leads to the first hypothesis H_1:

H_1: total water supply costs vary positively with distance and altitude.

To examine any peak - off-peak cost differentials, we state H_2:

H_2: peak period total costs exceed off-peak total costs.

A third hypothesis concerning costs is:

H_3: Scale economies in T&D are mainly determined by industrial water demands, as opposed to commercial or residential.

Empirical Approaches To Cost Function Estimation

The empirical approaches to these hypotheses are essentially the same. On the basis of the cost estimates generated from equations (4-8) and (4-15) above, the following relationship was estimated:

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[a] J. Johnston, Statistical Cost Analysis, New York: McGraw-Hill, 1960.

(4-17) $TC = f(Q, L, A)$

where TC = total cost of water supply:

Q = quantity, hundreds of cubic feet, CCF;

L = distance from the treatment plant to a point in the service area, feet; and

A = the altitude, feet.

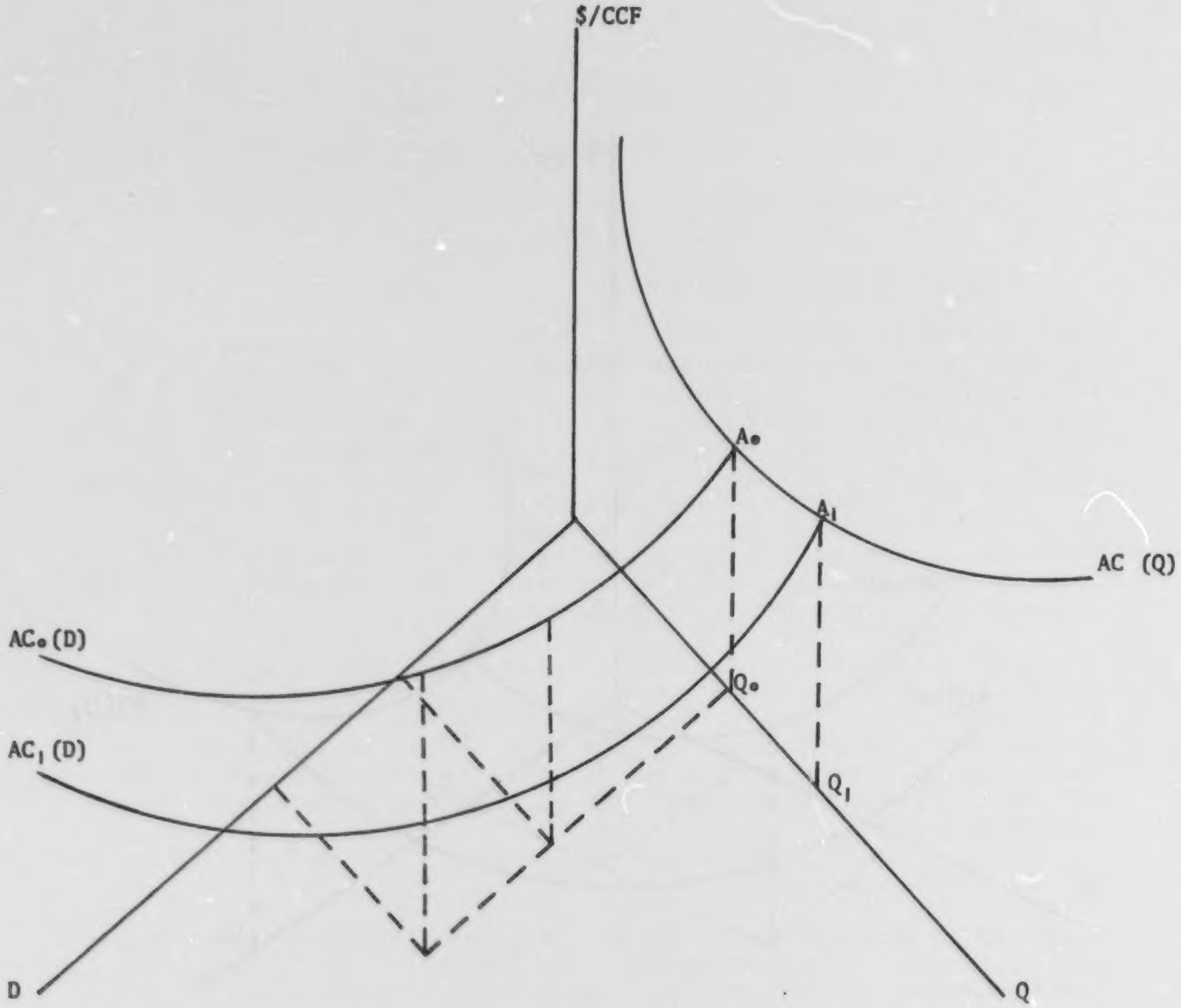
The total cost function may be employed in testing all three hypotheses for the data samples taken in each service zone for each user group. In other words, all the consumers in a service zone are stratified by customers class, thus permitting separate analyses. Therefore, estimation of cost equation (4-17) above may be performed for each user group in each zone for both peak and off-peak periods. This is expected to provide information on the effect of distance and topography on cost as well as possible economies and diseconomies of scale, the variation in cost between peak and off-peak periods, and the differences in water supply costs among user groups.

An alternative empirical approach may also be taken for estimation of their relationship which may provide a clearer view of the impact of distance and topography on cost. By using an average cost approach ($/CCF) as a method of holding the influence of Q constant, more reliability from the estimates may be obtained. Therefore, the alternative form of the above equation is:

(4-18) $AC = g(L, A)$,

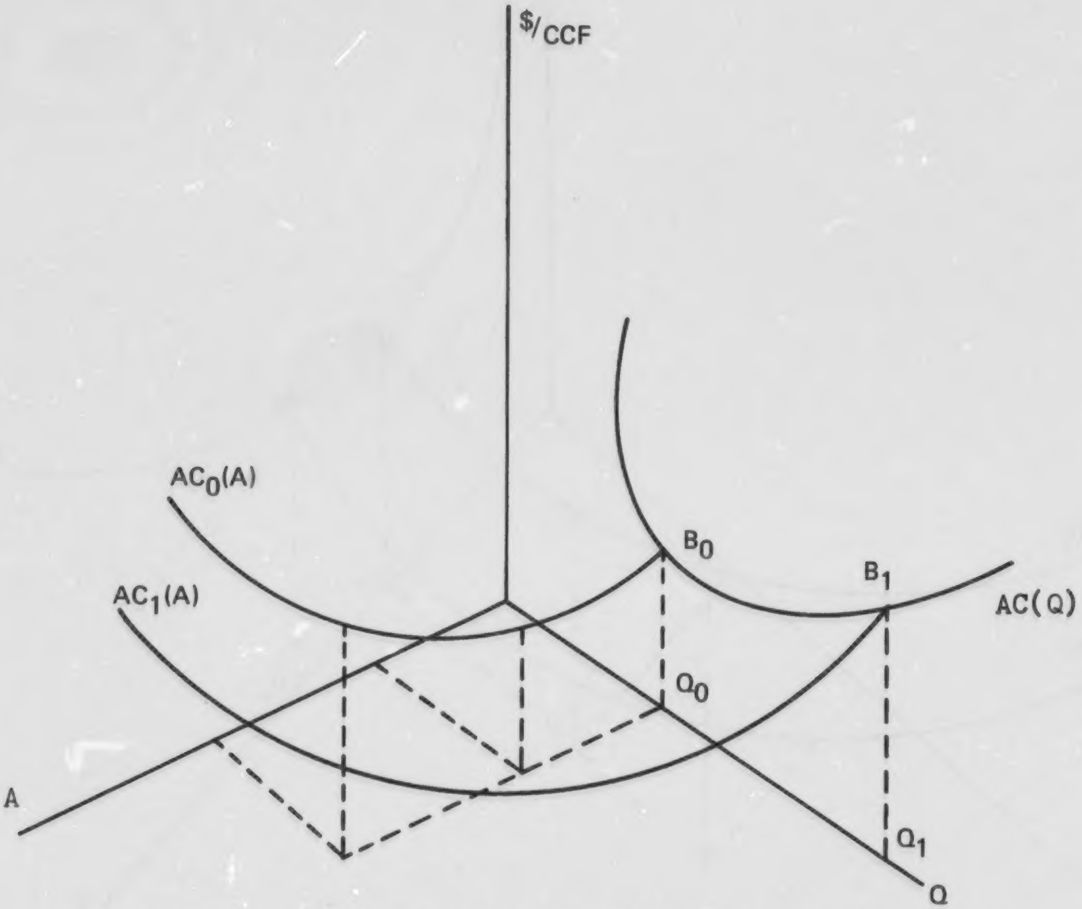
where AC is average cost, $/CCF. Figures 11 and 12 graphically depict the relationship of equation (4-18) to the traditional textbook average cost curve. The concentration is not on the traditional average cost, though the dimension is $/CCF. Instead, the relationship represents total cost with respect to distance and altitude for a hundred cubic feet of water. This may provide a better view of the impact of distance and altitude on cost.

The appropriate, functional form of the equation will be linear, logarithmic, or exponential depending upon the degree of normality of the data after a transformation as seen in a scattergram of the data points. A logarithmic transformation of a multiplictive specification of the equations readily gives estimates of the economy of scale parameter. In order to highlight the spatial aspects of the relevant T&D cost function,


$/CCF
A₀
A₁
AC (Q)
AC₀ (D)
AC₁ (D)
Q₀
Q₁
D
Q

Pt. A_0 represents the value of AC(Q), the traditional average cost relationship, for which flow Q_0 creates AC_0 (D). A different flow, Q_1, incurs a new A_1 and AC_1 (D).

Figure 11. Relationship of distance cost to a typical average cost curve.


$/CCF
AC0(A)
AC1(A)
B0
B1
AC(Q)
Q0
Q1
A
Q

This graph depicts the same type of relationship for altitude at flows Q_0 and Q_1.

Figure 12. Relationship of altitude cost to typical average cost curve.

computer generated maps of the dependent variables will also be presented. For the data points selected in the service area of the CWW, information on the following variables was collected or generated: (a) the quantity consumed at each data point for peak and off-peak periods, (b) the total cost of that quantity supplied to each data point, (c) the cost per hundred cubic feet of water for peak and off-peak periods, (d) the distance along the pipeline between the treatment plant and the data point, (e) and the change in altitude between the treatment plant and the data point.

Major Hypotheses: Cost-Rate Differentials

A policy of uniform zonal rate setting may allow significant inter-areal and intra-areal subsidization, and user cross subsidization within a customer class and perhaps among classes. The possibility of subsidization increases if cost is significantly affected by distance or topography. Thus, for a given quantity, uniform zonal average cost pricing could lead to higher rates than costs near the central treatment plant and lower rates than costs farther from the treatment plant. Thus, one would expect that those living closest to the treatment plant subsidize (on a unit basis) those who live farther from it. It is hypothesized therefore:

H_4: the CWW earns revenue surpluses on customers close to the A&T facility, and incurs deficits on those farther away.

Another hypothesis treats the question of the presence of cross user or customer class subsidies, as where industrial users might be subsidized by residential users, or vice versa.

H_5: the CWW incurs revenue deficits on industrial and commercial water supply, and surpluses on residential supply.

It should be pointed out that such a result may occur not so much because of cost differences, but because of the rate structure (declining block rates), discussed below. For no such subsidization to occur, rates would have to be tailored exactly to costs.

Lastly, an examination of the costs of delivering water during peak and off-peak periods, may reveal subsidies between peak and off-peak periods. If significant differences exist in the cost of supplying water between peak and off-peak periods, with an unchanging rate structure, then the following hypothesis may be supported:

H_6: Peak period water users are subsidized by off-peak users.

Of course, to some extent, these will be the same customers, who may in fact prefer to have level billing.

Empirical Approaches to the Analysis of Cost-Rate Differentials

The basic approaches to the analysis of cost-rate differentials include (1) computer generation of maps for broad-brush analysis of the spatial differentials uncovered, and (2) more precise estimates for specific (unidentified) accounts (customers) as a function of the spatial variables and customer class. This is performed for both peak and off-peak periods.

The maps and specific estimates are generated by comparing revenues from the data points with the cost information generated by the analyses discussed above.

The data required for this analysis consists of four elements; revenue during the peak and off-peak periods for the data points, the rate structure, the cost values for the data points for peak and off-peak periods, and the statistical results of the empirical work discussed in the section on cost functions.

Data Collection

We present a brief description of the data acquisition procedures employed in this study as a guide to future studies and to aid critics.

Data for this project was collected from the 1973 records of the Cincinnati Water Works. Unfortunately, it was not available in a form readily adaptable for this research.

The final data requirements as specified in the previous section consisted of: revenue, quantity consumed, and cost of supply information for each user group during the peak and off-peak periods for the data points selected; the distance along the pipeline and the change in altitude between the treatment plant and each data point; and the rate structure existing for the time of the study.

The preliminary data collection process was quite involved. The process began by dividing the service area into ten zones on the basis of direction of water flow and location of pumping stations as noted earlier. This was justified because each zone could be considered a small service area. This breakdown did not facilitate computation, but did add greater depth and disaggregation to the empirical analysis since cost curves could then be estimated for each zone. Also, cost variation over the area of the zone could be analyzed.

Once the zones were defined, a random sample of residential, commercial, and industrial users for each zone was drawn. This initially involved the determination of which customer accounts belonged in which group. Unfortunately, of the approximately 188,000 records, there was no clear user group demarcation. At the time of this study, the Cincinnati Water Works had two major classifications of customers: commercial monthly billed and quarterly billed. The commercial monthly billed accounts consisted of the larger users numbering about 1700 in total. The quarterly billed accounts could be broken into two groups based upon a family unit coding system which identifies the number of family units connected through that account (meter). If an account possessed a number less than or equal to 98, it was considered residential. For those classified 99, the customer account either had 99 families or the user was industrial, commercial or unclassifiable at the time of coding. The accounts coded 99 totaled approximately 8300. This total group of 1700 commercial monthly billed accounts and 8300 quarterly billed with a family units code of 99 were analyzed, categorized, and coded with a four-digit Standard Industrial Code (SIC). Once completed, four divisions of the approximate ten-thousand accounts could be made:

a) residential users to be included in the quarterly accounts are those with a family unit code of 98 or less, SIC code of zero or 6513;

b) commercial accounts with SIC code from 5000 to 8999;

c) industrial accounts with SIC code from 0100 to 4999;

and

d) other accounts with SIC code from 9100 to 9999.

The "other" accounts contained such users as schools, churches, hospitals, parks, and government buildings. This segment was not analyzed because of the wide diversity in water use among the users.

From this demarcation of accounts, each user group could be identified. The next step involved allocation of account numbers to service zones. It was found that census tracts could easily be associated to one zone or another and that the account numbers of the Water Works corresponded to census tract boundaries. On this basis, all the accounts particular to any zone could be determined for sampling of the user groups in connection with the SIC coding noted above. Once the records were entered and stratified into segments, one for each of the ten zones and three user groups, thirty random samples could be drawn. In order to maintain a sample size of at least thirty, samples greater than thirty records were taken. This allowed for deletion of those records on which information was incomplete.

Of the thirty samples, six were deleted. Three were dropped because one zone was too small to be able to obtain any significant variation in distance or altitude. The other three of the six deleted samples, all industrial samples, did not contain thirty users. In all cases, those samples dropped from the analysis came from the smallest service zones of the Cincinnati Water Works. Of the remaining twenty-four samples, there were a total of 805 sample points, (see Table 4). Given the sampled accounts, with specific addresses, it was then possible to compute the cost of delivering water to the points, for peak and off-peak periods.

The following procedure was used to identify the period. Based on monthly records for total water pumped records for the years 1965-1975, a monthly moving average was created to calculate monthly indices of water pumpage. The resulting distribution (Figure B) of the indices identified the peak and off-peak periods as the third and first quarter, respectively, of the yearly cycle. Quarters are identified here because no finer time dimension in the records of the Water Works exists for customer account records except the 1700 monthly billed accounts. Based on this then, the consumption and revenue records for the peak and off-peak periods could be collected for each sample point.

Having obtained the sample sets and data points, the remaining data needed for analysis were the cost of supply in peak and off-peak periods. The preliminary data collection process was also quite involved.

All transmission pipelines (greater than or equal to 16 inches in diameter) and their diameters were identified along with all remaining capital facilities such as pumping stations, storage tanks and the treatment plant. The historical cost of each element was recorded. Distribution pipeline capital and maintenance cost was included, but each line was not identified in the same manner as transmission lines. This element was ignored because of the inability to assign flows to those pipes. Finally total metered water flow for the entire system for each census tract was collected for the peak and off-peak quarters.[3] Assuming that the demands of all the census tracts must be supplied, representative water flow is each transmission pipe could be determined for an average day in the peak and off-peak quarters. Once the flows in each pipe were identified, costs of supply could be calculated through the use of equations (4-8)

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[3] The dimension of the water flow was converted from CCF/quarter to CCF/day to facilitate comparisons, as some quarters contain more days than others.

TABLE 4

NUMBER OF DATA POINTS STRATIFIED BY SERVICE ZONE AND USER CLASSIFICATION

Zone Label	Residential	Commercial	Industrial	Total in Zone
A	D	D	D	—
B1	31	34	D	65
B2	32	31	D	63
C1a	32	42	36	110
C1b	28	28	D	56
C2	30	30	33	93
C3a	39	30	36	105
C3b	30	42	32	104
C4a	30	42	33	105
C4b	39	32	33	104

TOTAL 805

Notes:

Total Sample Size user group:

1. Residential = 291
2. Commercial = 311
3. Industrial = 203

D ≡ deleted sample

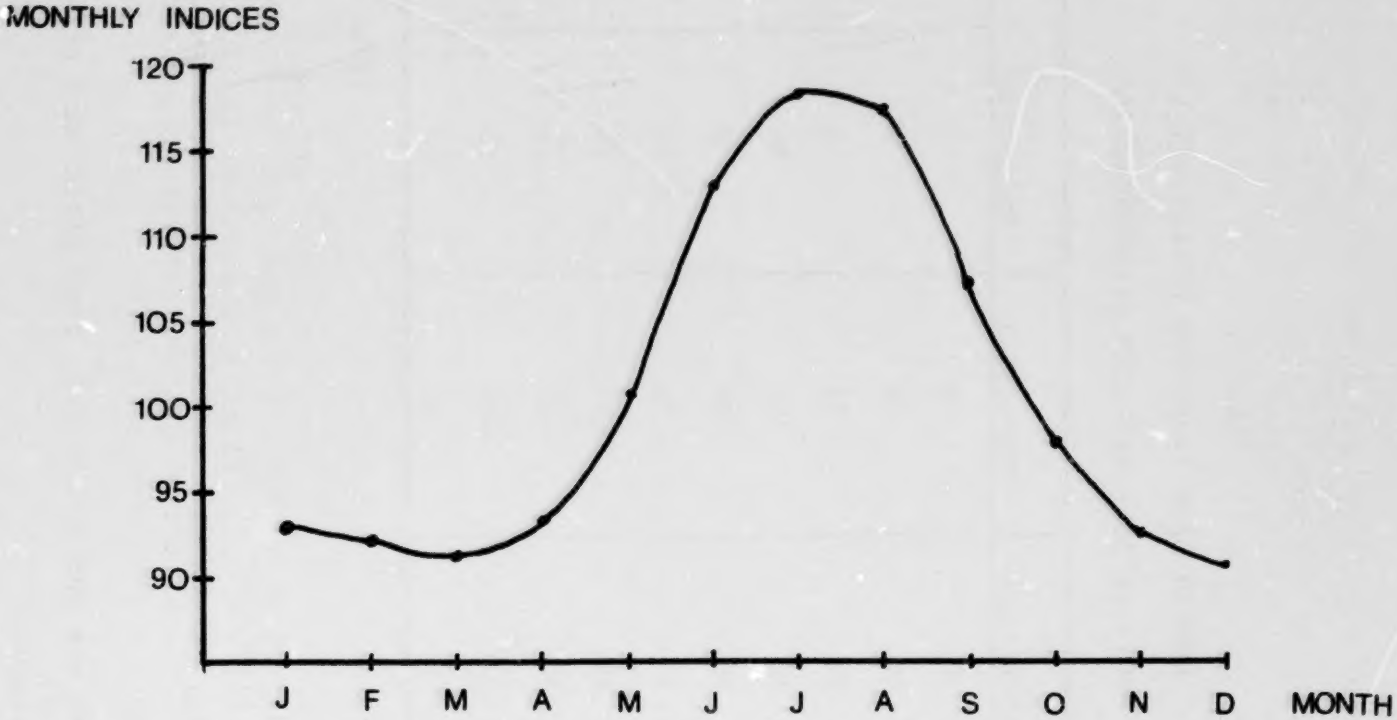

Figure 13. Monthly indices based on water pumpage for 1965-1975.

and (4-17) from the earlier discussion.[4]

Given those equations, total cost was calculated for varying distances and altitudes by adding together the cost of the separate components for both time periods for each sample point. To ensure that all cost elements were included, the costing procedure was made to balance with the annual report of the Cincinnati Water Works. These cost calculations also required simplyfying assumption for isolation of the effects of distance and altitude on cost. This assumption sets selected engineering factors constant. Specifically, by setting water pressure, pump efficiency, and the Chezy coefficient of pipe friction (C-factor) at a constant average value,[5] inconsistencies in the calculated data could be reduced if not eleiminated. If those constants were allowed to vary, it is possible that conflicting values of cost could be calculated for similar distances and altitudes in the same service zone. Then, the relationship between cost of water supply and distance/altitude would depend upon the distribution of water pressure, pump efficiency, and pipe quality. These variables do affect cost, but it was judged that the cost of obtaining the additional information would be greater than the increased precision would justify.

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[4] Capital costs per day for the peak period were calculated on the basis of the cost of the existing system. Capital costs per day for the off-peak period were calculated for a system capacity scaled down by the ratio of off-peak flow to peak flow. Once the proportion of capacity necessary was acquired, capital costs for the off-peak could be determined. Specifically, the capital cost for smaller transmission lines was calculated simply by using what it actually cost the Cincinnati Water Works for pipes of that size. Capital costs for pumping station and treatment were slightly more involved. Using the .6 rule of thumb noted by Moore (see literature review) and the following formula:

$T_K = aK^b$ where T_K = total capital cost,
K = capacity,
b = .6, and
a = a parameter; total off-peak capital cost can be determined. First set K and T_K at their peak period values and solve for "a". Finally, substitute in off-peak K. Using "a" and "b", off-peak capital cost is determined. In this manner, two complete capital systems for water supply could be established.

[5] Pressure was set at 100 psi, pump efficiency at 90% and C-factor at 100.

The last data element is the water rate structure in effect consists simply of the rate structure in effect during 1973, (see Table 5). Only those rates referring to inside Cincinnati and outside Cincinnati but inside Hamilton County are applicable to this study.

TABLE 5. CINCINNATI WATER WORKS WATER RATES EFFECTIVE APRIL 1, 1969.

MINIMUM CHARGES

		Inside Cincinnati		Outside Cincinnati in Hamilton and Clermont Counties		Butler and Warren Counties	
Meter Size	Number of Family Units	Monthly	Quarterly	Monthly	Quarterly	Monthly	Quarterly
5/8 inch	1	$ 2.50	$ 4.50	$ 5.00	$ 9.00	$ 5.75	$ 10.35
3/4 inch	2 or 3	2.80	5.40	5.60	10.80	6.45	12.40
1 inch	4 or 5	3.50	7.50	7.00	15.00	8.05	17.25
1-1/2 inch	6 thru 12	4.50	10.50	9.00	21.00	10.35	24.15
2 inch	13 thru 20	7.00	18.00	14.00	36.00	16.10	41.40
3 inch	21 thru 50	9.00	24.00	18.00	48.00	20.70	55.20
4 inch	55 thru 115	12.00	33.00	24.00	66.00	27.00	75.00
6 inch	116 thru 250	25.00	75.00	50.00	150.00	57.00	170.00
8 inch	over 250	35.00	105.00	70.00	210.00	80.00	240.00
10 inch		40.00	120.00	80.00	240.00	92.00	270.00
12 inch		40.00	120.00	80.00	240.00	92.00	270.00

TABLE 5. CONTINUED

COMMODITY CHARGES

		Inside Cincinnati Rate	Outside Cincinnati in Hamilton and Clermont Counties Rate	Butler and Warren Counties Rate
		Per 100 Cubic Feet		
In excess of 1,000 cubic ft. but not in excess of 60,000 cubic ft.	In excess of 2,000 cubic ft., but not in excess of 180,000 cubic feet.	20¢	35¢	40¢
In excess of 60,000 cubic ft., but not in excess of 1,000,000 cubic ft.	In excess of 180,000 cubic feet, but not in excess of 3,000,000 cubic feet.	16¢	28¢	32¢
In excess of 1,000,000 cubic ft.	In excess of 3,000,000 cubic feet.	12¢	21¢	24¢

SECTION V

EMPIRICAL RESULTS

GENERAL PURPOSES

This chapter presents and reviews the empirical results generated in the quantitative phase of the study. Following the division developed in the previous chapter, there are two basic analyses presented: (a) cost functions and (b) cost-rate differentials. Findings are presented on costs among customer classes, peak and off-peak period costs, the relationship of cost to distance and altitude, and the cost-rate differentials.

PART A: COST ANALYSES

Cost Functions Disaggregated by Customer Class

For this analysis, 24 separate samples were drawn. The data were extensively analyzed for normality. Both the square root and logarithmic transformation improved the normality of the data, but in general, the logarithmic transformation was better.

With this data and the generated cost estimates, the following relationships (from the hypotheses in Section IV) were examined:

(5-1) $TC_1 = f(Q)$

(5-2) $TC_2 = g(L,A,Q)$

(5-3) $TC_3 = h(L,A)$

where TC_1 and TC_2, are total costs;

Q is quantity (CCF);

L is distance in feet;

A is net altitude in feet;

TC_3 is sum of A&T plus T&D per CCF (i.e., an average cost).

Scattergrams of the data were constructed to choose appropriate functional forms. The forms examined (in terms of the independent variables) were linear, square root and multiplicative (log-linear). For each sample, and each customer class (residential, commercial and industrial) 3 peak and 3 off-peak equations were estimated, utilizing step-wise regression analyses.

The multiplicative form will be emphasized here, as it tends to fit the data best. An added advantage of this log-linear form is that the estimated regression coefficients are also the elasticity estimates, and are particularly useful in an examination of cost economies with respect to quantity, distance and altitudes.

Table 6 presents the estimates for total cost as function of quantity alone (equation 5-1). The coefficients for lu Q are the total cost elasticities, which are defined ad d lu TC/d lu Q = ϵ. For example, for equation 1 in Table 6, $\epsilon = 0.2734$, which means that for the peak period, a 10% increase in quantity of water consumed across the sample led to a 2.7% increase in cost. This can be more readily seen by noting that in the equation TC = aQ (as in Table 6), $TC/Q = aQ^{\epsilon}/Q = aQ^{\epsilon-1}$ = SRAC (shortrun average cost). Thus any $\epsilon < 1$ implies a negatively sloped short run average cost curve, i.e. d(Ae)/dQ $= (\epsilon-1)\ aQ^{\epsilon-2}$ which is negative, for $\epsilon < 1$.

It is important to emphasize, that the estimates are based on a system with fixed capital facilities, and so these estimates are for short run total and average costs. The term "scale economies", conversely, applies to situations in which capital facilities are variable. The only insight into scale economies presented in this study would come from a comparison of peak and off-peak elasticity estimates.

A general finding here is that the estimated cost elasticities for residential customers as a group are smaller, meaning that average cost to residential customers as a group declines more rapidly than to industrial or commercial customers. While this does seem contradictory of what is usually expected, it is plausible if one recognizes that, since we are considering residences, industries and places of commerce as classes, the total quantity of capital in place to serve residences is greater than for the other sectors, and it is thus reasonable for the cost economies to appear as they have. This finding does need to be investigated further.

TABLE 6. IMPACTS OF QUANTITY ON TOTAL COST OF DELIVERED WATER.

Zone C_{1a} - Peak Period

1. Residential

$$\text{Ln}\ (TC_1) = \underset{(.1079)}{-2.2406} + \underset{(.0214)}{2.734}\ \text{Ln}\ (Q) \quad DF = 30;\ R^2 = .844$$

2. Commercial

$$\text{Ln}\ (TC_1) = \underset{(.5689)}{-1.597} + \underset{(.0447)}{.7075}\ \text{Ln}\ (Q) \quad DF = 40;\ R^2 = .862$$

3. Industrial

$$\text{Ln}\ (TC_1) = \underset{(.4674)}{-1.576} + \underset{(.0337)}{.8061}\ \text{Ln}\ (Q) \quad DF = 34;\ R^2 = .944$$

Zone C_{1a} - Off-Peak Period

4. Residential

$$\text{Ln}\ (TC_1) = \underset{(.2819)}{-2.5395} + \underset{(.0539)}{.1191}\ \text{Ln}\ (Q) \quad DF = 30;\ R^2 = .140$$

5. Commercial

$$\text{Ln}\ (TC_1) = \underset{(.4683)}{-1.634} + \underset{(.0420)}{.6984}\ \text{Ln}\ (Q) \quad DF = 40;\ R^2 = .874$$

6. Industrial

$$\text{Ln}\ (TC_1) = \underset{(.4827)}{-1.6215} + \underset{(.0363)}{.8162}\ \text{Ln}\ (Q) \quad DF = 34;\ R^2 = .937$$

Zone C_2 - Peak Period

7. Residential

$$\text{Ln}\ (TC_1) = \underset{(.3689)}{-2.1903} + \underset{(.0906)}{.2883}\ \text{Ln}\ (Q) \quad DF = 28;\ R^2 = .265$$

8. Commercial

$$\text{Ln}\ (TC_1) = \underset{(.5273)}{-1.5554} + \underset{(.0524)}{.6284}\ \text{Ln}\ (Q) \quad DF = 28;\ R^2 = .837$$

9. Industrial

$$\text{Ln}\ (TC_1) = \underset{(.5587)}{-1.674} + \underset{(.0515)}{.8074}\ \text{Ln}\ (Q) \quad DF = 31;\ R^2 = .888$$

Zone C_2 - Off-Peak Period

10. Residential

$$\mathrm{Ln}\ (TC_1) = \underset{(.3393)}{-2.0609} + \underset{(.0807)}{.3542}\ \mathrm{Ln}\ (Q) \quad DF = 28;\ R^2 = .408$$

11. Commercial

$$\mathrm{Ln}\ (TC_1) = \underset{(.711)}{-1.692} + \underset{(.0829)}{.7115}\ \mathrm{Ln}\ (Q) \quad DF = 28;\ R^2 = .725$$

12. Industrial

$$\mathrm{Ln}\ (TC_1) = \underset{(.5694)}{-1.4025} + \underset{(.0466)}{.6483}\ \mathrm{Ln}\ (Q) \quad DF = 31;\ R^2 = .862$$

Note: all coefficients significant at 95% or higher.

Another important finding can be seen by comparing peak-period costs with off-peak. A usual expected result is to find that costs decline more rapidly for the peak-period investments. This would require the elasticity to be smaller for the peak period equations. The results in Table 6 are mixed. In zone C_{1a} it is true for the industrial class (0.8061 vs 0.8162) but they are not significantly different statistically. Similar conclusions apply to residential and commercial classifications in zone C_2. Conversely, for residences in zone C_1, the off-peak elasticity is less, and significantly so. This suggests diseconomies of scale (the peak vs off-peak comparisons represent the only case in which we can draw inferences about scale economies, as mentioned earlier). A pricing system which did not take such scale diseconomies into account could be said to be inefficient.

Estimation of equation 5-2 was performed to examine the relative effects of quantity, distance, and net altitude. No statistically significant effects were found for the distance and altitude variables, in spite of the fact that there was little to no multicollinearity between the distance and altitude variables. In virtually all cases the quantity variable accounted for most of the explain variance. This occurred because there is relatively much more variation in Q than in A and L_c around TC.

Equation 5-3 represents an attempt to circumvent the unequal variances by standardizing TC into TC per CCF (dividing by Q). This makes the dependent variable an average cost measure, but as a sum of A&T, T&D costs per CCF, with plant size fixed. As before, the only scale implications that can be drawn are from the comparison of peak and off-peak costs. These results are presented in Table 7. There are a number of implications of the results presented in Table 7. At present, it is not possible to relate distance to total cost, as it would be necessary to segregate the samples by TC and D, so that an analysis could be performed for those sample points for which the restriction $\partial TC/\partial D > 0$ holds.

First, net altitude, in general, is not an important determinant of the average costs of delivered water for the CWW area, but it is important where the typography is especially hilly, as in zones C_2 and C_{3b} (see Figure 9). Another fact with respect to the altitude variable present in Table 7 is that its magnitude is less than the coefficient for distance, which reflects the fact that, while the CWW supply area is hilly, it is not so hilly as to cause altitude to rival distance in costs, especially in transmission costs, where these two factors are principally important.

TABLE 7. IMPACTS OF ALTITUDE AND DISTANCE ON AVERAGE COSTS OF DELIVERED WATER.

Zone C_{1b} - Peak Period

1. Residential

$$\text{Ln}\ (TC_3) = \underset{(.006)}{-19.669} + \underset{(.088)}{1.636}\ \text{Ln}\ (D) - \underset{(.0332)^{ns}}{.0341}\ \text{Ln}\ (A) \qquad \begin{matrix} DF = 25 \\ R^2 = .962 \end{matrix}$$

2. Commercial

$$\text{Ln}\ (TC_3) = \underset{(.001)}{-20.949} + \underset{(.0054)}{1.732}\ \text{Ln}\ (D) - \underset{(.005)^{ns}}{.0028}\ \text{Ln}\ (A) \qquad \begin{matrix} DF = 25 \\ R^2 = .999 \end{matrix}$$

Zone C_{1b} - Off-Peak Period

3. Residential

$$\text{Ln}\ (TC_3) = \underset{(.007)}{-25.515} + \underset{(.1126)}{2.171}\ \text{Ln}\ (D) - \underset{(.0423)^{ns}}{.0663}\ \text{Ln}\ (A) \qquad \begin{matrix} DF = 25 \\ R^2 = .964 \end{matrix}$$

4. Commercial

$$\text{Ln}\ (TC_3) = \underset{(.0027)}{-27.9695} + \underset{(.0170)}{2.3666}\ \text{Ln}\ (D) - \underset{(.0157)^{ns}}{.0294}\ \text{Ln}\ (A) \qquad \begin{matrix} DF = 25 \\ R^2 = .999 \end{matrix}$$

Zone C_2 - Peak Period

5. Residential

$$\text{Ln}\ (TC_3) = \underset{(.110)}{-5.415} + \underset{(.0314)}{.2994}\ \text{Ln}\ (D) + \underset{(.0291)}{.0874}\ \text{Ln}\ (A) \qquad \begin{matrix} DF = 27 \\ R^2 = .794 \end{matrix}$$

6. Commercial

$$\text{Ln}\ (TC_3) = \underset{(.114)}{-5.1693} + \underset{(.0441)}{.2723}\ \text{Ln}\ (D) + \underset{(.0271)}{.0891}\ \text{Ln}\ (A) \qquad \begin{matrix} DF = 27 \\ R^2 = .635 \end{matrix}$$

7. Industrial

$$\text{Ln}\ (TC_3) = \underset{(.182)}{-4.2226} + \underset{(.0730)}{.2161}\ \text{Ln}\ (D) + \underset{(.0286)^{ns}}{.0164}\ \text{Ln}\ (A) \qquad \begin{matrix} DF = 30 \\ R^2 = .229 \end{matrix}$$

Zone C_2 - Off-Peak Period

8. Residential

$$\text{Ln}\ (TC_3) = \underset{(.192)}{-5.9439} + \underset{(.0548)}{.3618}\ \text{Ln}\ (D) + \underset{(.0507)^{ns}}{.0710}\ \text{Ln}\ (A) \qquad \begin{array}{l} DF = 27 \\ R^2 = .635 \end{array}$$

9. Commercial

$$\text{Ln}\ (TC_3) = \underset{(.165)}{-6.1139} + \underset{(.0637)}{.3479}\ \text{Ln}\ (D) + \underset{(.0392)}{.123}\ \text{Ln}\ (A) \qquad \begin{array}{l} DF = 27 \\ R^2 = .585 \end{array}$$

10. Industrial

$$\text{Ln}\ (TC_3) = \underset{(.238)}{-4.625} + \underset{(.0954)}{.2522}\ \text{Ln}\ (D) + \underset{(.0374)^{ns}}{.0242}\ \text{Ln}\ (A) \qquad \begin{array}{l} DF = 30 \\ R^2 = .192 \end{array}$$

Zone C_{3b} - Peak Period

11. Residential

$$\text{Ln}\ (TC_3) = \underset{(.035)}{-7.982} + \underset{(.0458)}{.5128}\ \text{Ln}\ (D) + \underset{(.0493)}{.1051}\ \text{Ln}\ (A) \qquad \begin{array}{l} DF = 27 \\ R^2 = .830 \end{array}$$

12. Commercial

$$\text{Ln}\ (TC_3) = \underset{(.0239)}{-8.7062} + \underset{(.0322)}{.5707}\ \text{Ln}\ (D) + \underset{(.0235)}{.1174}\ \text{Ln}\ (A) \qquad \begin{array}{l} DF = 39 \\ R^2 = .904 \end{array}$$

13. Industrial

$$\text{Ln}\ (TC_3) = \underset{(.0471)}{-9.233} + \underset{(.0887)}{.6228}\ \text{Ln}\ (D) + \underset{(.0472)}{.103}\ \text{Ln}\ (A) \qquad \begin{array}{l} DF = 29 \\ R^2 = .630 \end{array}$$

Zone C_{5b} - Off-Peak Period

14. Residential

$$\text{Ln}\ (TC_3) = \underset{(.0503)}{-9.475} + \underset{(.065)}{.641}\ \text{Ln}\ (D) + \underset{(.070)}{.1223}\ \text{Ln}\ (A) \qquad \begin{array}{l} DF = 27 \\ R^2 = .789 \end{array}$$

15. Commercial

$$\text{Ln}\ (TC_3) = \underset{(.0271)}{-10.0089} + \underset{(.0365)}{.686}\ \text{Ln}\ (D) + \underset{(.0266)}{.126}\ \text{Ln}\ (A) \qquad \begin{array}{l} DF = 39 \\ R^2 = .912 \end{array}$$

16. Industrial

$$\text{Ln}\ (TC_3) = \underset{(.063)}{-10.785} + \underset{(.1196)}{.7704}\ \text{Ln}\ (D) + \underset{(.0637)^{ns}}{.0914}\ \text{Ln}\ (A) \qquad \begin{array}{l} DF = 29 \\ R^2 = .589 \end{array}$$

Note: All coefficients except those marked by ns are significant at 95% level or more.

A second major implication is that distance is seen to be a major determinant of the AC of delivering water, and the high AC elasticities (up to 2.3) imply substantial diseconomies to distance, (although we have no direct measure of the total cost elasticity). The apparent finding of substantial diseconomies with respect to distance indicates that there are rather definite limitations to the economic size of water supply areas. Of course, an economic area cannot be defined on the basis of one set of cost estimates, as it would be necessary to compare the costs with the costs of serving outlying areas from another location in order to define the boundary of a service area. A critical factor then will be the trade-off involving in A&T scale economies with the diseconomies of T&D. A third finding of the regressions in Table 7 is that off-peak AC elasticities are greater than the peak elasticities for the distance variable, that is, the diseconomies are greater for the off-peak users. While more investigation of this point is in order, this indicates "scale" economies in peak facilities with respect to distance, meaning that the diseconomy for peak facilities rises less rapidly than for off-peak.

In general, it appears that significant cost economies of scale can exist in transmission of water in addition to the economies usually associated with the treatment process. But, these results also imply that cost elasticity varies over the total service area (increasing with respect to distance) and that limits do exist to the economic area of a water utility.

Aggregated Cost Functions

In this section, we examine various combinations of the data. Such combinations, however, typically create statistical problems, one of which is heteroskedasticity (unequal variances among the observations) the presence of which violates least squares assumptions. Upon examination of the data utilized here, little to no variation was found in the extimate of variance for distance and altitude variance from one sample to the next. In addition, the differences among the variances that do exist diminish after a logarithmic transformation of the data is performed. Much variation in the variances for quantity exists from one sample to the next and especially across user groups. But, this also decreases upon a logarithmic transformation, not only across user groups, but also over service areas.

A total of 16 combinations of the 24 samples was conducted. Nine of these involve aggregating all user groups within a zone. Five of the remaining seven were divided into residential, commercial, and industrial segments. Two of five were residential: one for the two service zones east of the treatment plant (RES), the other for the seven service zones north and west of the plant (RWS). Likewise, two other data sets (CES and CWS)

TABLE 8. PEAK AND OFF-PEAK COST ELASTICITIES FOR QUANTITY.

Zone $C1_a$ - Peak Period

$$\begin{array}{llll} \text{Ln}\ (TC_1) = & -1.5491 & +\ .7253\ \text{Ln}\ (Q) & DF = 108 \\ & (.503) & (.0236) & R^2 = .897 \end{array}$$

Zone $C1_a$ - Off-Peak Period

$$\begin{array}{llll} \text{Ln}\ (TC_1) = & -1.6341 & +\ .7238\ \text{Ln}\ (Q) & DF = 108 \\ & (.5367) & (.0274) & R^2 = .866 \end{array}$$

Zone B_2 - Peak Period

$$\begin{array}{llll} \text{Ln}\ (TC_1) = & -1.6974 & +\ .5774\ \text{Ln}\ (Q) & DF = 63 \\ & (.524) & (.0396) & R^2 = .771 \end{array}$$

Zone B_2 - Off-Peak Period

$$\begin{array}{llll} \text{Ln}\ (TC_1) = & -1.8841 & +\ .5118\ \text{Ln}\ (Q) & DF = 63 \\ & (.4626) & (.0459) & R^2 = .664 \end{array}$$

Zone B_2 - Off-Peak Period

$$\begin{array}{llll} \text{Ln}\ (TC_1) = & -1.8841 & +\ .5118\ \text{Ln}\ (Q) & DF = 63 \\ & (.4626) & (.0459) & R^2 = .664 \end{array}$$

Note: All coefficients significant at the 95% level or more.

were created by partition of the commercial data. The remaining data set (DN) of the five included all industrial sample points north and west of the treatment plant. No industrial samples to the east had been collected. The final two data sets (TES and TWS) of the 16 contained all the data points east of the treatment plant in one group and all data points north and west in the other. Linear, square root and multiplicative specifications were tested, but as before, the multiplicative form gave the best results, and these are presented here.

Results from estimation of equation 5-1 in Table 8 indicate the existence of cost economies with respect to distance for all zones. Estimated cost elasticity values for the nine zones range from .5596 to .7449 for the peak period and from .5118 to .7238 for the off-peak period. In addition, though the peak period values are greater than off-peak, they are statistically not significantly different from one another.

For the other seven samples, the regression results show that the cost elasticities of quantity for commercial and industrial users are significantly greater than that for residential samples for peak and off-peak periods, though all of their estimates are very much below a value of one. The regression equations in Table 9 for samples RWS (all residential sample points to the west and north of the treatment plant) and DN (all industrial sample points to the west and north of the treatment plant) and DN (all industrial sample points to the west and north of the treatment plant) indicate the difference in cost elasticity estimates.

TABLE 9. RESIDENTIAL AND INDUSTRIAL SAMPLES.

Sample RWS - Peak Period

$$\mathrm{Ln}\ (TC_1) = -1.925 + .4211\ \mathrm{Ln}\ (Q) \quad DF = 226$$
$$(.3205)\ (.0233) \quad R^2 = .591$$

Sample RWS - Off-Peak Period

$$\mathrm{Ln}\ (TC_1) = -1.988 + .3769\ \mathrm{Ln}\ (Q) \quad DF = 226$$
$$(.3656)\ (.0259) \quad R^2 = .484$$

Sample DN - Peak Period

$$\mathrm{Ln}\ (TC_1) = -1.5074 + .7463\ \mathrm{Ln}\ (Q) \quad DF = 201$$
$$(.606)\quad (.0192) \quad R^2 = .882$$

Sample DN - Off-Peak Period

$$\text{Ln}\ (TC_1) = -1.4795 + .7166\ \text{Ln}\ (Q) \quad DF = 201$$
$$(.609) \quad (.0198) \quad R^2 = .867$$

Note: All coefficients significant at the 95% level or more.

Estimation of equation 5-2 again provided no information on the relation between total cost and the distance/altitude variables, as in general, the estimater of the distance/altitude parameters were statistically insignificant. Quantity again accounted for the greater part of the variance explained.

Estimation of equation 5-3 using the data from the 16 samples provides some interesting results. This form examines only the association between cost per CCF and the distance/ altitude variables. The following five results appear the most important.

First, for the nine zones, cost elasticity estimates increase as the distance to the zone increases (see Table 10). Using any of the paths through the nine zones as outlined in Figure 9, it is easy to see that along each path, the cost elasticity value increase.

Secondly, the difference between off-peak and peak average cost elasticities increases for the more distant zones. This implies that the diseconomies of distance increase more rapidly for off-peak costs than for peak, which is consistent with the earlier findings of the AC elasticities.

Thirdly, no significant relationship between cost and altitude was detected.

Fourthly, as seen in Table 11, industrial cost elasticity based on the combined samples is found to be significantly lower (at better than the 99% level) with respect to distance than the cost elasticities for residential and commercial sample sets. This was not evident in the zonal breakdown for user groups.

Fifthly, an examination of peak versus off-peak cost differentials for samples TES (all sample points east of the treatment plant) and TWS (all sample points west and north of the treatment plant), reveals that a statistical difference between peak and off-peak differentials exist for the system as a whole (see Table 12), but the numerical difference is not very large. As shown in Table 13, the 95% confidence interval overlap.

TABLE 10. AVERAGE COST ELASTICITIES ARRAYED BY DISTANCE.

Zone Paths	Peak	Off-Peak	Difference
B_1	0.1367	0.1656	-0.0289
B_2	0.3095	0.2758	0.0337
C_{1a}	0.1735	0.1813	-0.0078
C_{1b}	1.7189	2.3406	-0.6217
C_{3a}	0.1482	0.1681	-0.0199
C_{3b}	0.5522	0.6796	-0.1274
C_{4a}	0.1159	0.1152	0.0007
C_{4b}	0.2824	0.3642	-0.0818

Note: These coefficients are for the distance variable in AC = f(A,D). All coefficients significant at 95% level or more.

TABLE 11. INDUSTRIAL AVERAGE COST ELASTICITIES.

Sample RWS - Peak Period

$$\begin{array}{llllll} \text{Ln}\ (TC_3) = & -6.256 & + .3976\ \text{Ln}\ (D) & + .042\ \text{Ln}\ (A) & DF = 225 \\ & (.149) & (.0224) & (.0052) & R^2 = .642 \end{array}$$

Sample RWS - Off-Peak Period

$$\begin{array}{llllll} \text{Ln}\ (TC_3) = & -6.6428 & + .4336\ \text{Ln}\ (D) & + .0459\ \text{Ln}\ (A) & DF = 225 \\ & (.176) & (.0264) & (.0062) & R^2 = .606 \end{array}$$

Sample DN

$$\begin{array}{llllll} \text{Ln}\ (TC_3) = & -4.215 & + .2158\ \text{Ln}\ (D) & + .0251\ \text{Ln}\ (A) & DF = 200 \\ & (.1051) & (.0181) & (.0035) & R^2 = .589 \end{array}$$

Sample DN

$$\begin{array}{llllll} \text{Ln}\ (TC_3) = & -4.459 & + .2387\ \text{Ln}\ (D) & + .0277\ \text{Ln}\ (A) & DF = 200 \\ & (.1276) & (.0220) & (.0042) & R^2 = .543 \end{array}$$

Note: All coefficients significant at the 95% level or better.

TABLE 12. PEAK AND OFF-PEAK AVERAGE COST ELASTICITIES.

Sample TES - Peak Period

$$\begin{array}{lllll} \text{Ln}\ (TC_3) = & -5.443\ + & .3652\ \text{Ln}\ (D)\ + & .0169\ \text{Ln}\ (A) & DF = 125 \\ & (.0656) & (.0154) & (.0063) & R^2 = .820 \end{array}$$

Sample TES - Off-Peak Period

$$\begin{array}{lllll} \text{Ln}\ (TC_3) = & -5.6377\ + & .3909\ \text{Ln}\ (D)\ + & .0067\ \text{Ln}\ (A) & DF = 125 \\ & (.1636) & (.0149) & (.0061) & R^2 = .846 \end{array}$$

Sample TWS - Peak Period

$$\begin{array}{lllll} \text{Ln}\ (TC_3) = & -5.4986\ + & .3321\ \text{Ln}\ (D)\ + & .0321\ \text{Ln}\ (A) & DF = 674 \\ & (.141) & (.0128) & (.0028) & R^2 = .576 \end{array}$$

Sample TWS - Off-Peak Period

$$\begin{array}{lllll} \text{Ln}\ (TC_3) = & -5.854\ + & .3651\ \text{Ln}\ (D)\ + & .0356\ \text{Ln}\ (A) & DF = 674 \\ & (.1636) & (.0149) & (.0032) & R^2 = .576 \end{array}$$

Note: All coefficients significant at 95% level or better, unless indicated.

TABLE 13. 95% CONFIDENCE LIMITS FOR DISTANCE COST ELASTICITIES.

	TES		TWS	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit
Peak	.3350	.3954	.3070	.3573
Off-Peak	.3617	.4201	.3359	.3943

In summary, a significant positive relationship was found to exist between distance and average cost, and less frequently between altitude and average cost. In addition, the elasticity of average cost with respect to distance was greater than one for one service zone.

Industrial water supply cost elasticity estimates with respect to quantity were found to be significantly greater than estimates for residential water supply while with respect to distance were lower than the residential estimates of elasticity. Estimates of commercial water supply elasticity were close to those for industrial with respect to quantity, yet close to residential estimates with respect to distance.

In examination of peak versus off-peak costs, the following results were obtained. No significant difference exists between peak and off-peak costs with respect to distance in a general formulation all zones combined, but important differences do occur in those zones most distant from the treatment plant. Also, peak cost elasticity of quantity was found to be generally greater than that for off-peak cost estimates.

PART B: COST-RATE DIFFERENTIALS

For the analysis of cost-rate differentials, we have chosen to examine the value of net revenue to the CWW for each account examined in the sample. A net revenue differential $(TR_i - TC_i)$ for each water account i is a cost-rate differential with its signs reversed, and multiplied by Q, the quantity of water consumed.

The current rate structure of the CWW does not differentiate among users in terms of differential costs (peak, off-peak, altitude, and for the most part distance), with the exception that users outside of the city are charged a high rate (see Table 5); but it does use a declining block rate schedule, which is supposed to reflect the presence of scale economies in water supply.

For an analysis of cost rate differentials, such a rate schedule would lead us to expect the following:

1 - Off-peak users are subsidizing peak users;

2 - Those accounts closest to the A&T facilities are subsidizing those more distant; and

3 - Small users are subsidizing large users.

However, despite the fairly detailed analyses conducted for this study, unequivocal answers will be difficult to come by. For example, when service zones were aggregated (Table 9), the peak cost elasticities were greater than the off-peak, but when disaggregated, as in Table 5, this pattern was sometimes reversed (c.f. zone C_2). Nonetheless, we shall endeavor to draw whatever generalizations seem valid.

Rate Structure and Overall Cost Elasticities by Customer

Table 14 presents data on actual water use by customer class for the CWW service area. This table averages peak and off-peak water use, and thus shows each group in the top rate block of Table 6. It is generally expected, however, that the incremental cubic foot of water consumed by residential customers will fall in the top rate block, commercial users in the second, and industrial users in the third. This data, compared with the

TABLE 14. MEAN WATER USE BY CUSTOMER CLASS.

User Group	Average Day Quarterly Mean Water Consumption	Rate Block Applicable for User Group
Residential	4266 cubic feet	Top
Commercial	50769 cubic feet	Top
Industrial	172224 cubic feet	Top

findings in Table 9 suggests that (1) even if industrial users paid the same incremental charge as residential consumers, since the industrial cost elasticity is greater than the residential, residential customers are subsidizing industrial users on an incremental basis; (2), if the typical large industrial user falls in the third (or lowest) rate block, then the subsidy is greater still. The exact and full impact of the subsidies would require more analysis. Thus, it appears that the CWW water structure does lead to such subsidization. Bringing rates into line with costs would require the use of the cost functions developed in Section IV.

Analysis of Computer Constructed Maps

In order to generate more detailed analysis regarding the presence and distribution of cost-rate differentials, the costs and revenues were computed for each sample point, and the resulting distributions were mapped. The boundaries of the resulting regions were determined by pre-set ranges for the differentials, and thus do not conform to the regions established for the purpose of the cost analyses reported above. The contour maps shown here have suppressed some of the detail in cost-rate differentials in order to present a clearer view of the patterns.

Delivered Cost Comparisons

Figures 14 and 15 present the spatial distribution of off-peak and peak period costs respectively for all classes combined. The range of values for the 6 regions indicate that cost of supply to region 4 is almost twice as much as that to region 1. Region denoted as 5 and 6 are even higher in supply cost, but represent a relatively small portion of the utility's service area. It appears, then, that a significant spatial difference in water supply costs does exist.

Two findings are of note. First, the peak and off-peak cost regions generated by this analysis do not correspond. There are substantial overlaps, but comparisons of the two maps show considerable shifting in the cost contours. Secondly, where region numbers do coincide, the peak-costs per CCF tend to be less than the off-peak. It should be noted however, that more variation exists on the peak map as well as a greater number of higher cost areas. Thus, comparison of a specific point on the two maps will frequently show the point experiencing higher peak-costs than off-peak, often the same, and seldom less. The equations for generating the cost estimates are equations 4-8 and 4-16, divided by the respective q_{ijk}.

These comparisons are complemented by Figure 16 and the associated Tables 15, 16 and 17. Milepoints are indicated, and the relevant peak and off-peak costs are noted--the information is the same as contained in Figures 14 and 15. Resource

TABLE 15. RESIDENTIAL NET REVENUES.

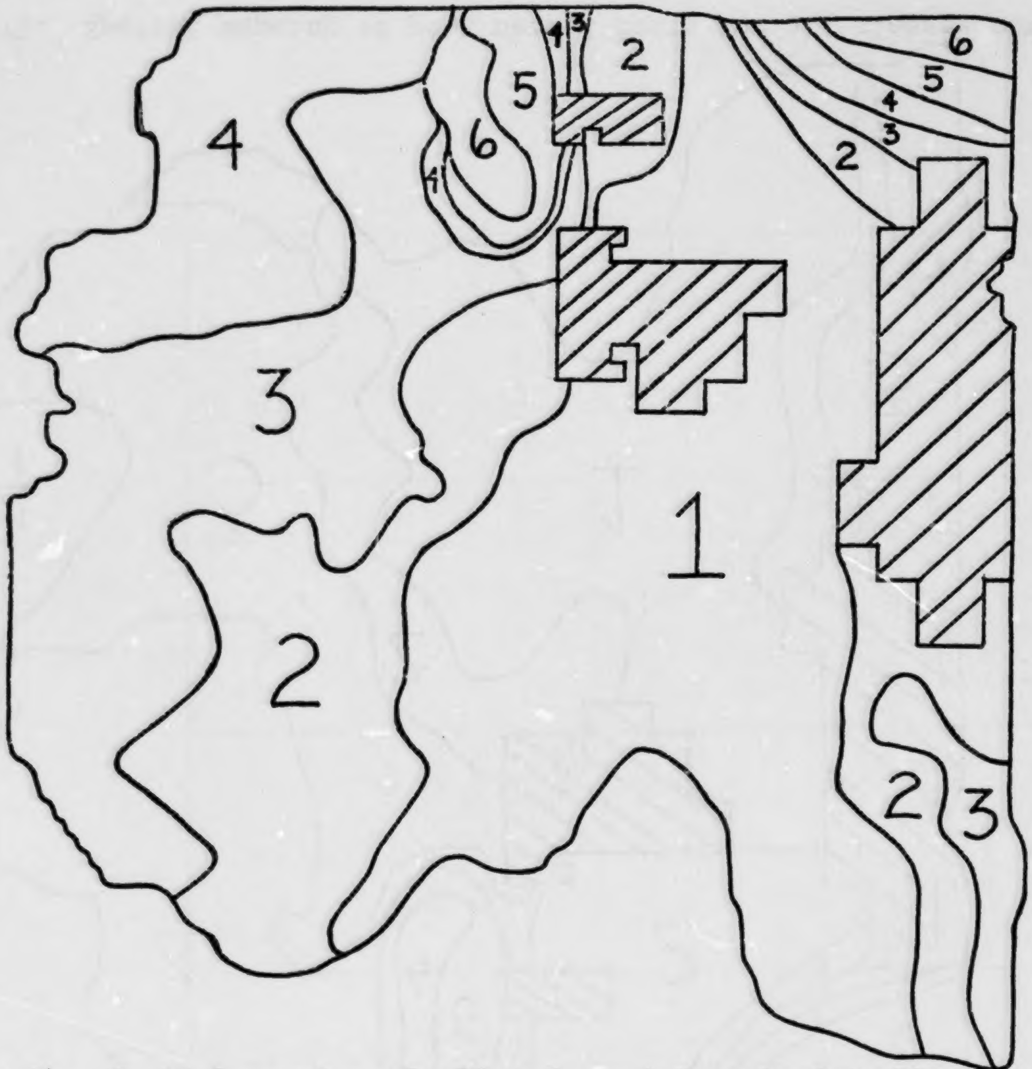
	Route C_1		Route C_3	
Mile-Point	Off-Peak	Peak	Off-Peak	Peak
0-1	.09 - .16	.11 - .18	.09 - .16	.11 - .18
1-2	0.00 - .09	.03 - .08	0.00 - .09	.03 - .08
2-3	0.00 - .05	.03 - .08	0.00 - .05	.03 - .08
3-4	0.00 - .05	.03 - .08	0.00 - .05	.03 - .08
4-5	.05 - .09	.03 - .08	.05 - .09	.03 - .08
5-6	.05 - .09	.03 - .08	0.00 - .05	.03 - .08
6-7	.05 - .09	.03 - .08	0.00 - .05	.03 - .08
7-8	.09 - .13	.08 - .11	0.00 - .05	.03 - .08
8-9	.09 - .13	.11 - .14	0.00 - .05	.03 - .08
9-10	.16 - .20	.18 - .21	.05 - .09	.03 - .08
10-11	.16 - .20	.18 - .21	.05 - .09	.08 - .11
11-12	.16 - .20	.18 - .21	.09 - .13	.14 - .18
12-13	.16 - .20	.14 - .18	.13 - .16	.14 - .18
13-14	.16 - .20	.14 - .18	.09 - .13	.11 - .14
14-15	.16 - .20	.18 - .21	.13 - .16	.14 - .18
15-16	.09 - .13	.11 - .21	.13 - .16	.14 - .18
16-17	0.00 - .05	.08 - .11	.13 - .16	.11 - .14
17-18	.05 - .09	.03 - .08	.09 - .13	.11 - .14
18-19	-	-	.09 - .13	.11 - .14
19-20	-	-	.09 - .13	.11 - .14
20-21	-	-	.13 - .16	.11 - .14
21-22	-	-	.09 - .13	.11 - .14

TABLE 16. COMMERCIAL NET REVENUES.

	Route C_1		Route C_3	
Mile-Point	Off-Peak	Peak	Off-Peak	Peak
0-1	.06 - .10	.08 - .11	.06 - .10	.08 - .11
1-2	.03 - .06	.02 - .05	.03 - .06	.02 - .05
2-3	-.01 - .03	-.02 - +.02	-.01 - +.03	-.02 - +.02
3-4	-.01 - +.03	-.02 - +.02	-.01 - +.03	-.02 - +.02
4-5	.03 - .06	-.02 - +.02	-.01 - +.03	-.02 - +.02
5-6	.03 - .06	.02 - .05	-.01 - +.03	-.02 - +.02
6-7	-.01 - +.03	-.02 - +.02	-.01 - +.03	-.02 - +.02
7-8	.03 - .06	.02 - .05	-.01 - +.03	-.02 - +.02
8-9	.03 - .06	.05 - .08	-.01 - +.03	-.02 - +.02
9-10	.10 - .14	.11 - .13	-.01 - +.03	-.02 - +.02
10-11	.10 - .14	.11 - .13	-.01 - +.03	.02 - .05
11-12	.10 - .14	.11 - .13	-.06 - -.01	-.02 - +.02
12-13	.10 - .14	.11 - .13	-.01 - +.03	.02 - .05
13-14	.10 - .14	.11 - .13	-.06 - .01	.02 - .05
14-15	.10 - .14	.11 - .13	+.03 - +.06	.02 - .05
15-16	.03 - .06	.05 - .11	+.03 - +.06	.08 - .11
16-17	-.01 - +.03	-.02 - +.05	+.03 - +.06	.08 - .11
17-18	-.06 - -.01	-.02 - +.02	+.03 - +.06	.08 - .11
18-19	-	-	-.06 - -.01	.02 - .05
19-20	-	-	-.01 - +.03	.02 - .05
20-21	-	-	.03 - .06	.05 - .08
21-22	-	-	.03 - .06	.05 - .08

TABLE 17. INDUSTRIAL NET REVENUES.

	Route C_1		Route C_3	
Mile Point	Off-Peak	Peak	Off-Peak	Peak
0-1	-.03 - +.01	-.04 - -.01	-.03 - +.01	-.04 - -.01
1-2	-.03 - +.01	-.04 - -.-1	-.03 - +.01	-.04 - -.01
2-3	-.03 - +.01	-.04 - -.01	-.03 - +.01	-.04 - -.01
3-4	-.03 - +.01	-.04 - -.01	-.03 - +.01	-.04 - -.01
4-5	-.03 - +.01	-.01 - +.01	-.06 - -.03	-.04 - -.01
5-6	-.06 - -.03	-.04 - -.01	-.06 - -.03	-.04 - -.01
6-7	-.03 - +.01	-.01 - +.01	-.06 - -.03	-.04 - -.01
7-8	-.03 - +.01	-.04 - -.01	-.06 - -.03	-.07 - -.04
8-9	-.06 - -.03	-.04 - -.01	-.06 - -.03	-.04 - -.01
9-10	-.03 - +.04	-.01 - +.01	-.06 - -.03	-.04 - -.01
10-11	.04 - .07	.04 - .06	-.06 - -.03	-.04 - -.01
11-12	.04 - .07	.04 - .06	-.06 - -.03	-.07 - -.07
12-13	.04 - .07	.04 - .06	-.06 - -.03	-.04 - -.01
13-14	.01 - .04	.04 - .06	-.03 - +.01	-.01 - +.01
14-15	.01 - .04	.01 - .04	-.03 - +.01	-.01 - +.01
15-16	.01 - .04	.01 - .04	-.03 - +.01	-.01 - +.01
16-17	.01 - .04	.01 - .04	-.03 - +.01	-.01 - +.01
17-18	.01 - .04	.01 - .04	-.03 - +.01	-.01 - +.01
18-19	-	-	-.06 - -.03	-.04 - -.01
19-20	-	-	-.06 - -.03	-.01 - +.01
20-21	-	-	-.03 - +.01	.01 - .04
21-22	-	-	-.03 - +.01	-.01 - +.01



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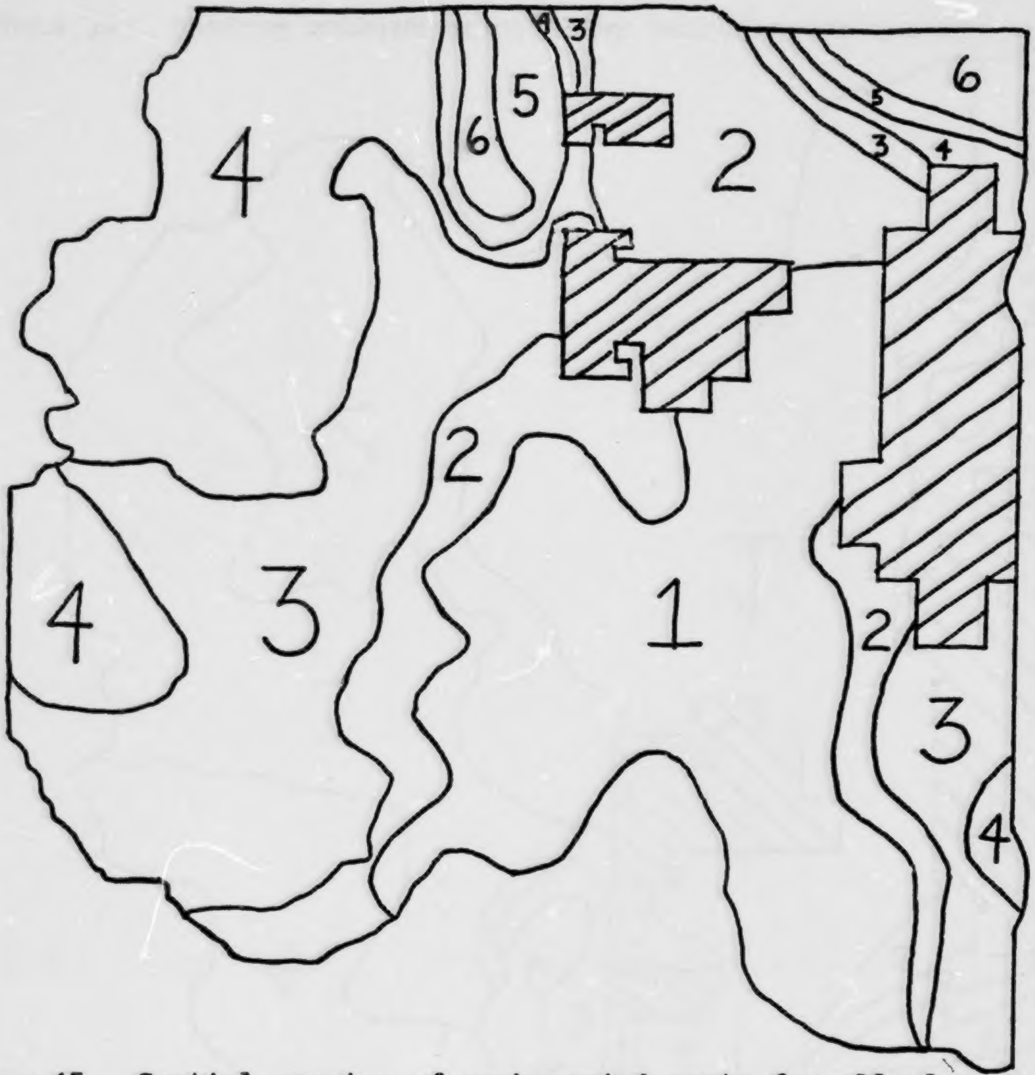
3

AREA	OFF-PEAK COST RANGES
1	.14 to .18
2	.18 to .22
3	.22 to .25
4	.25 to .29
5	.29 to .34
6	.34 to .40

Figure 14. Spatial mapping of off-peak period costs for all classes combined.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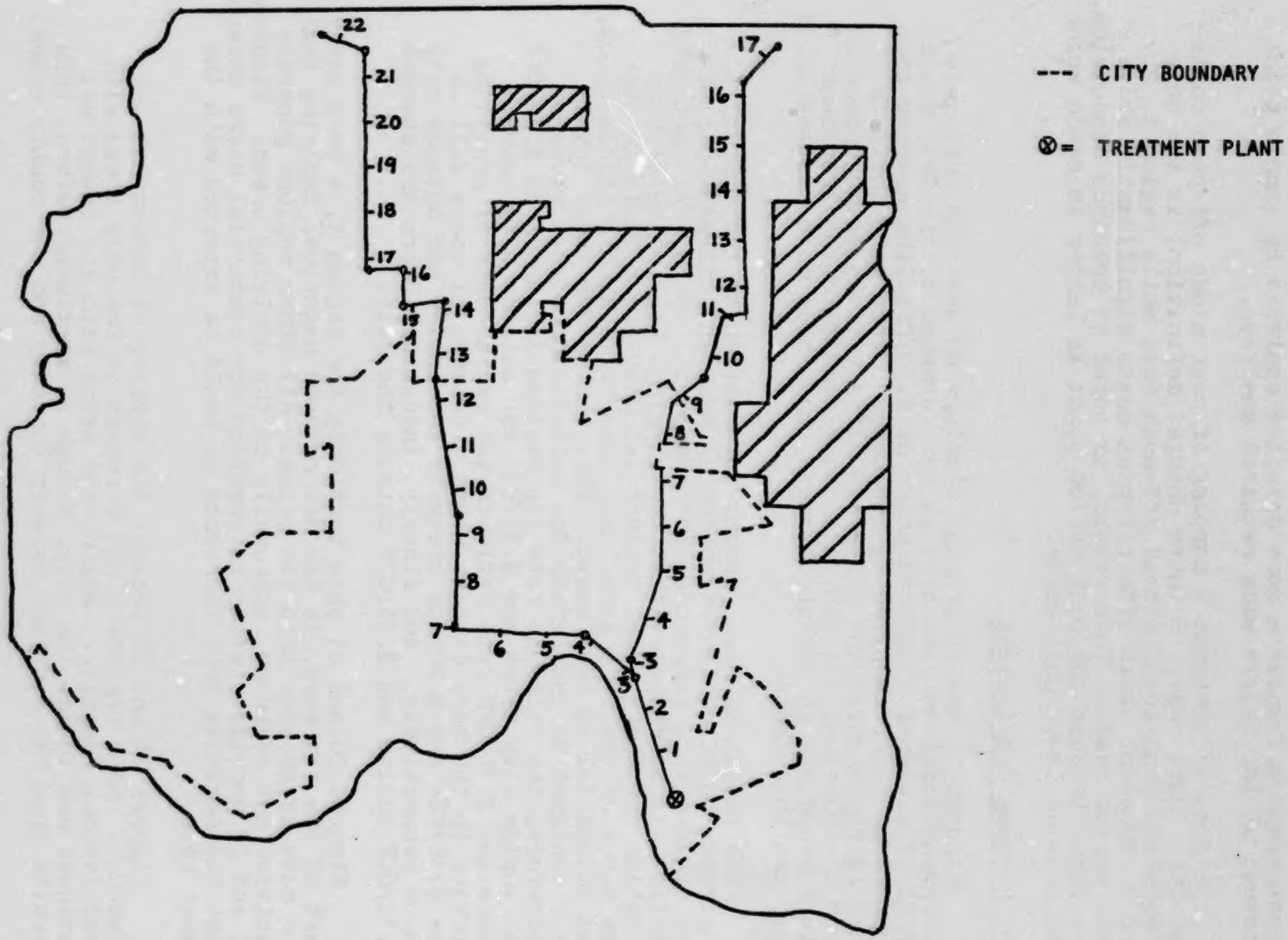
4

AREA	PEAK COST RANGES
1	.14 to .17
2	.17 to .20
3	.20 to .22
4	.22 to .25
5	.25 to .29
6	.29 to .33

Figure 15. Spatial mapping of peak period costs for all classes combined.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--- CITY BOUNDARY
⊗= TREATMENT PLANT

Figure 16. Water main routes with indicated mile points.

constraints prevented a more detailed analysis by sample point instead of the fairly wide required analyses.

Figure 17 presents a mapping of peak minus off-peak costs per CCF. Here region 6 (note changed definition) is the only area where peak costs exceed off-peak cost while region 1, 2, and 3 represent areas with off-peak costs significantly above peak period costs. This result, as noted in previous discussion, may occur because the peak period plant is larger in scale which can provide lower unit costs.

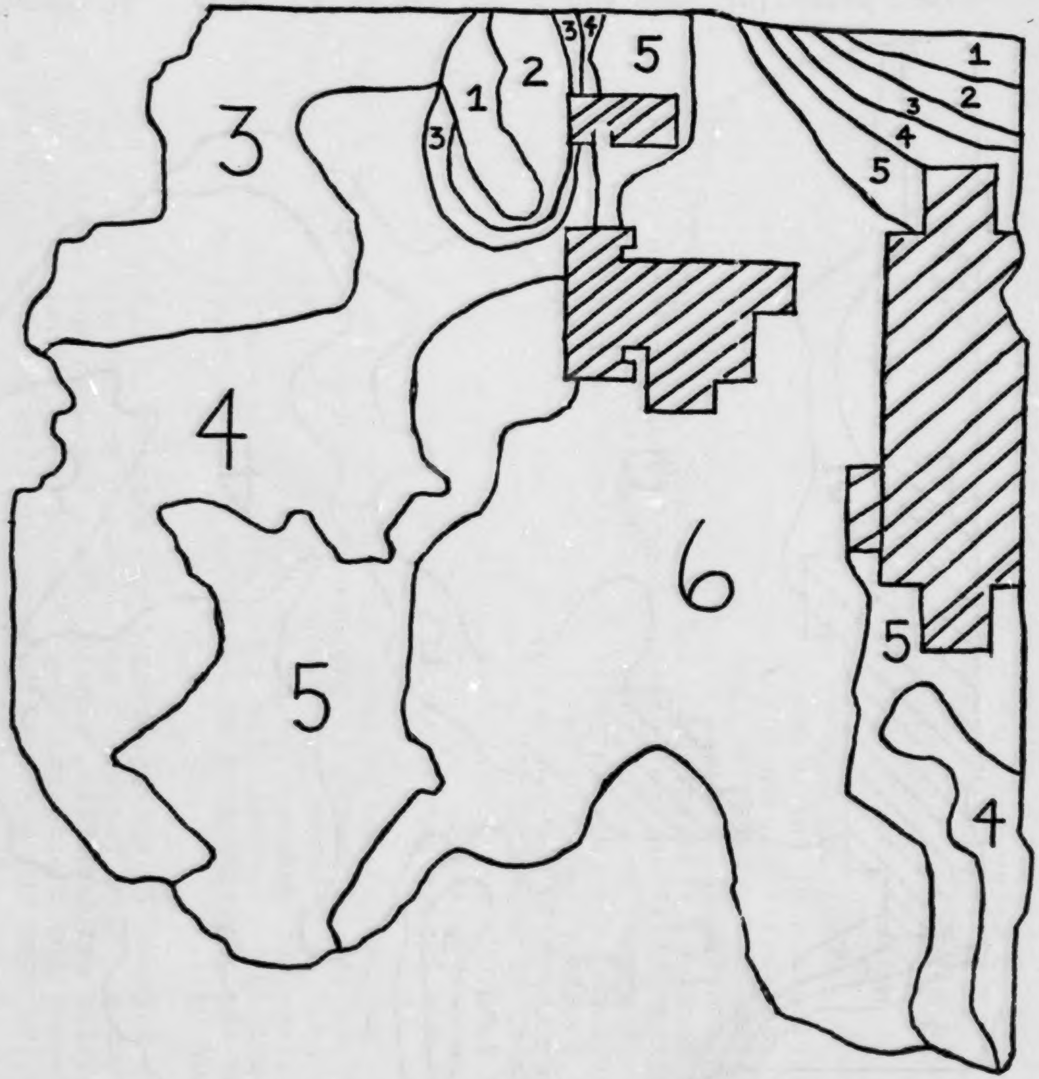
Net Revenue Comparisons

Figures 18 and 19 present findings on what the cost-rate differentials (analyzed here as net revenues to the CWW) would be if it employed a uniform price of $.20/CFF (the average cost per CCF of water supplied by the CWW). These maps indicate that fairly significant cost-rate differentials would appear in such a situation. In general, those closer to the treatment plant would pay in excess of costs, and those more distant would pay less than costs.

The remaining maps present information on the spatial distribution of net revenues during peak and off-peak periods for residential, commercial and industrial users. As mentioned earlier, it is expected that the marginal unit of water consumption for the typical residential user group falls in the top block of the rate structure, commercial in the middle block, and industrial in the lowest. Thus, rates for those levels were assigned to each group for calculation of net revenue. Therefore, the relevant rate for residential users in $.20/CCF for inside city users and $.35/CCF for outside city users, where the $.35/CFF rate reflects the extra costs of providing service to the more distant users. Commercial users fall in the $.16/CCF and $.28/CCF brackets for inside and outside city users respectively. And finally, industrial users are charged $.12/CCF inside and $.21/CCF outside the city.

Figures 20 and 21 show that only for region 1, a very small part of the two maps, is the net revenue negative, implying that the cost is greater than the price. All other regions generate positive net revenues, especially in the outlying areas. Figures 22 and 23 provide similar information for commercial users except that the negative area increases as would be expected with the lower rate.

Figures 24 and 25 present the mapping of industrial net revenues. Here regions 5 and 6 remain as the only areas with positive net benefits. Again, the areas with the lowest net revenues are inside the city, though as mentioned before, this results from the contrast between the city and the county rates.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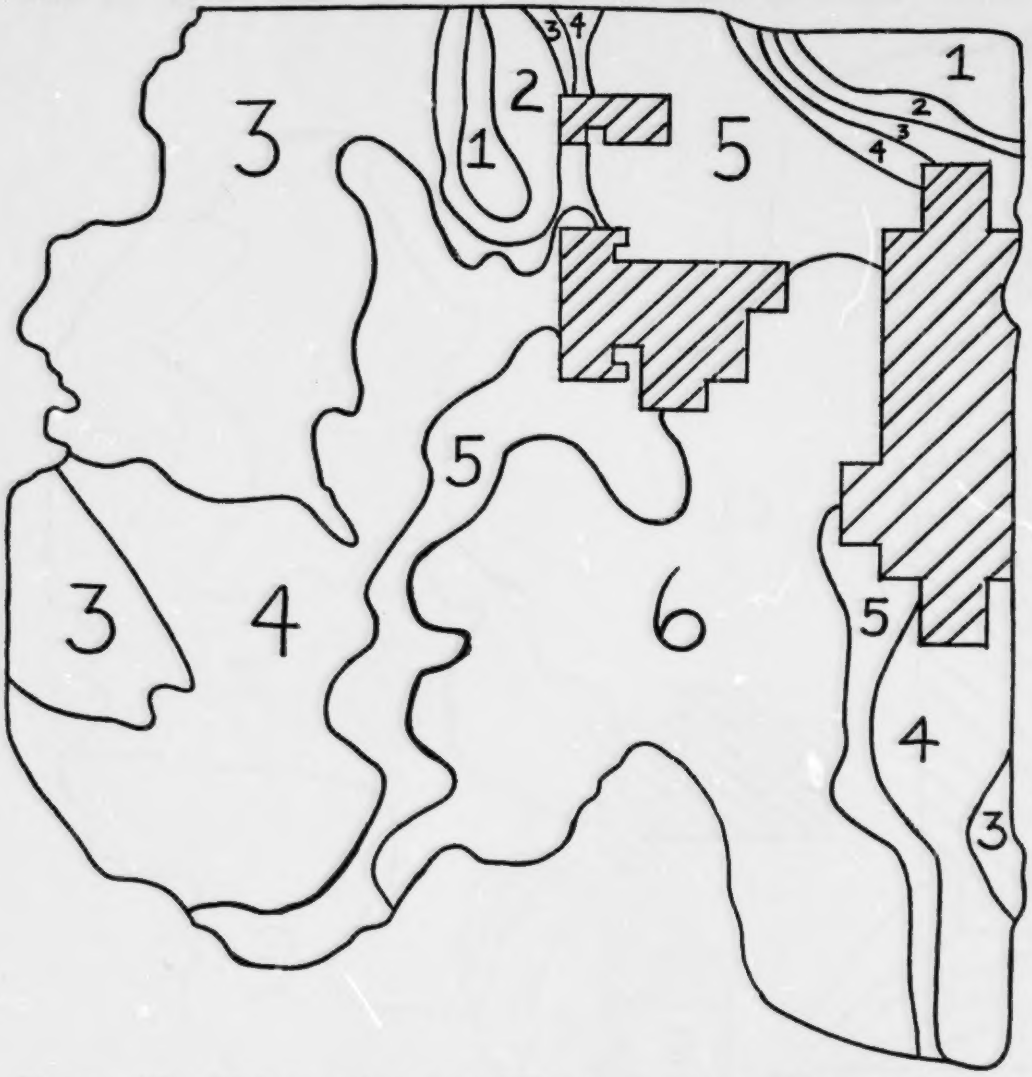
AREA	WATER RATES PER CCF MINUS DELIVERED COSTS
1	-.20 to -.14
2	-.14 to -.09
3	-.09 to -.05
4	-.05 to -.02
5	-.02 to .02
6	.02 to .06

Figure 17. Water rates per CCF minus off-peak delivered costs.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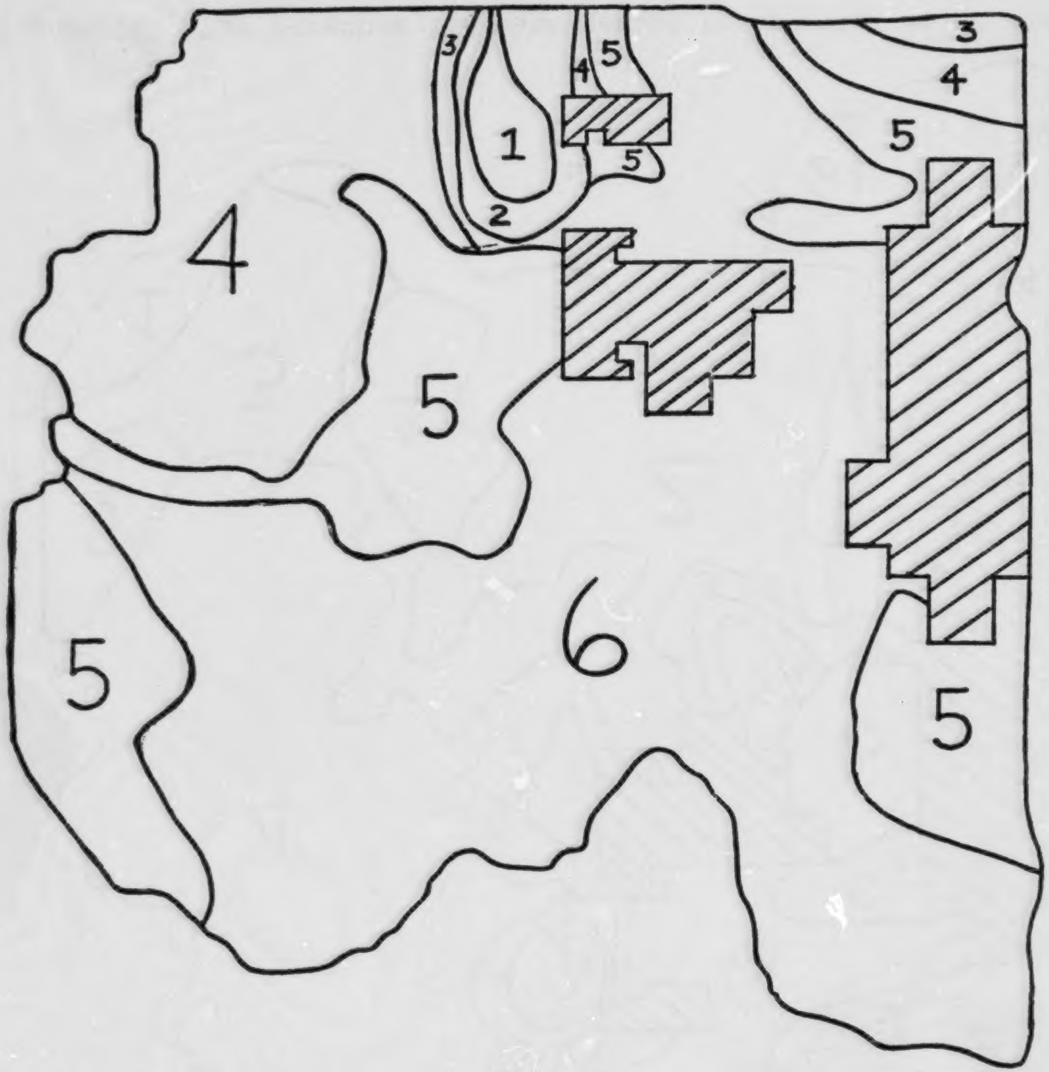
3

AREA	WATER RATES PER CCF MINUS DELIVERED COSTS
1	-.13 to -.09
2	-.09 to -.05
3	-.05 to -.02
4	-.02 to 0.0
5	0.0 to .03
6	.03 to .06

Figure 18. Water rates per CCF minus peak delivered costs.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5
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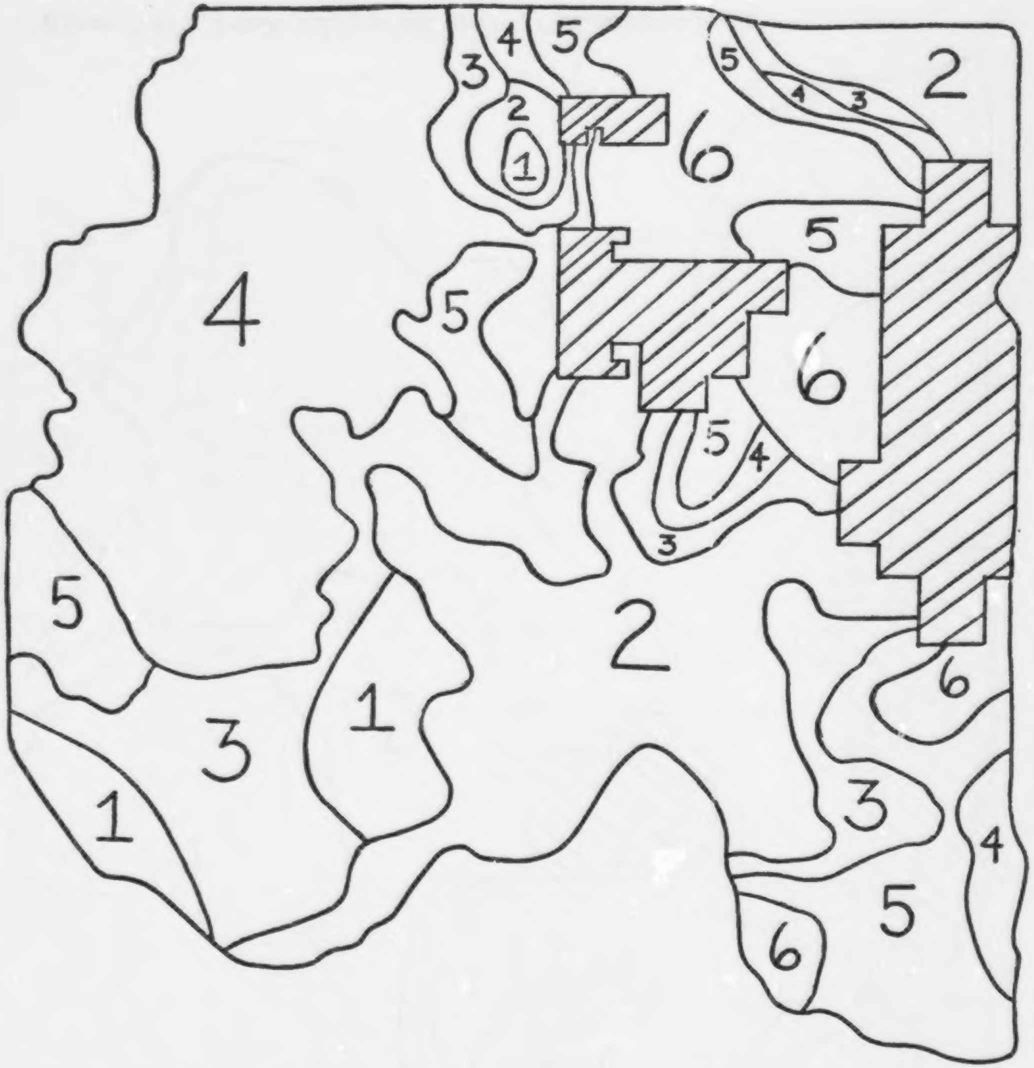
5
5

AREA	PEAK MINUS OFF-PEAK COST
1	-.08 to -.06
2	-.06 to -.04
3	-.04 to -.03
4	-.03 to -.02
5	-.02 to 0.0
6	0.0 to .01

Figure 19. Peak/off-peak cost differentials.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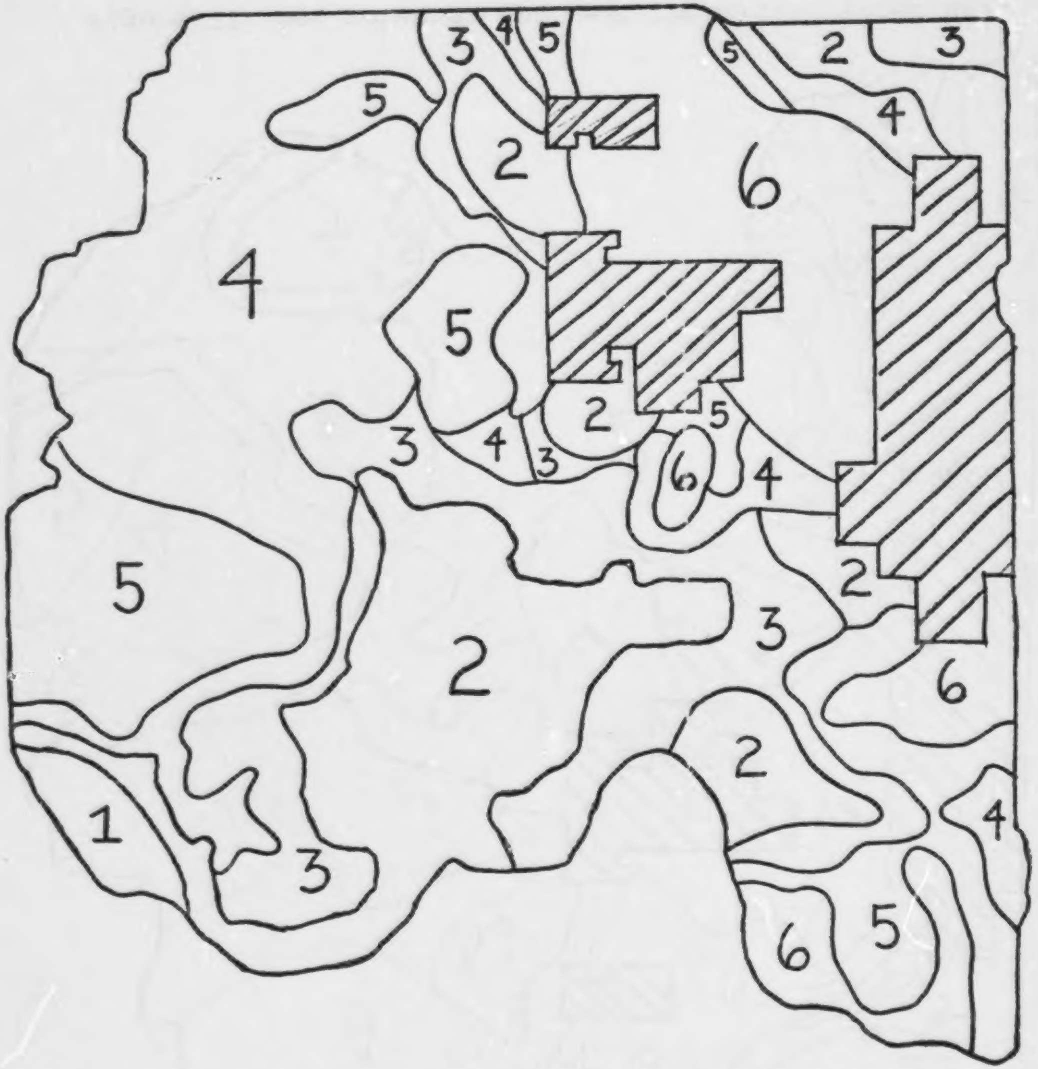
AREA	REVENUES MINUS PEAK COSTS-RESIDENTIAL
1	-.01 to .03
2	.03 to .08
3	.08 to .11
4	.11 to .14
5	.14 to .18
6	.18 to .21

Figure 20. Net revenues for peak period residential water use.



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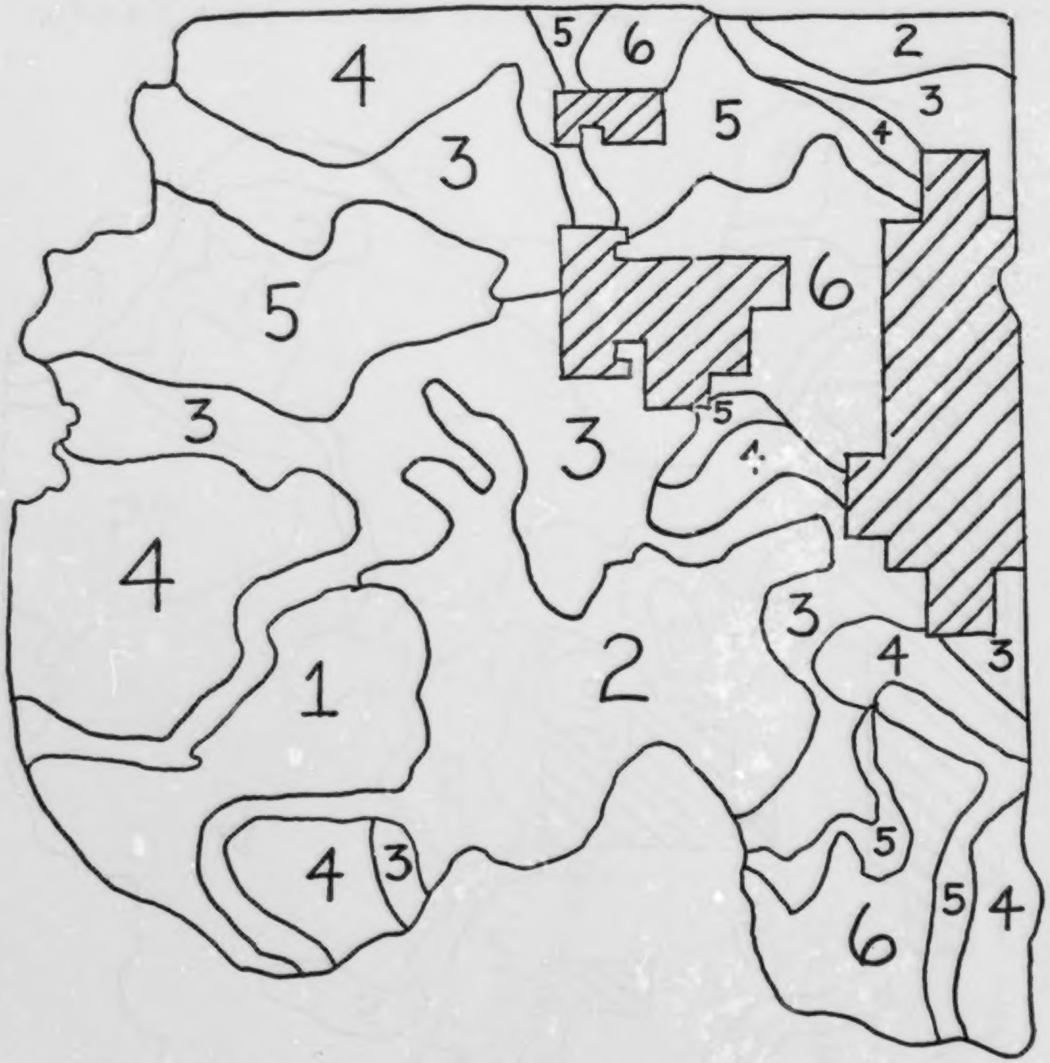
AREA	REVENUES MINUS OFF-PEAK COSTS RESIDENTIAL
1	-.05 to 0.0
2	0.0 to .05
3	.05 to .09
4	.09 to .13
5	.13 to .16
6	.16 to .20

Figure 21. Net revenues for off-peak residential water use.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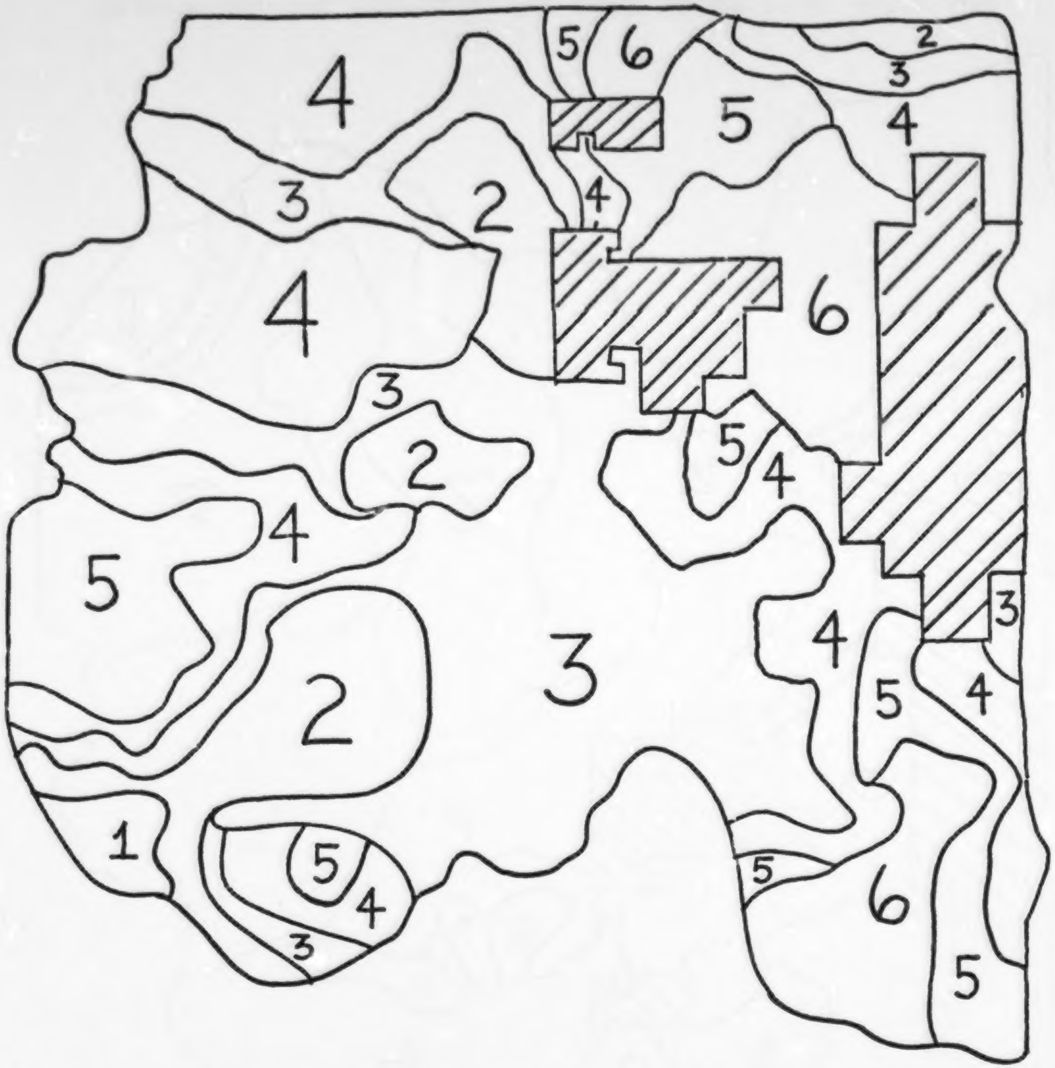
AREA	REVENUES MINUS PEAK COSTS COMMERCIAL
1	-.06 to -.02
2	-.02 to .02
3	.02 to .05
4	.05 to .08
5	.08 to .11
6	.11 to .13

Figure 22. Net revenues for peak commercial water use.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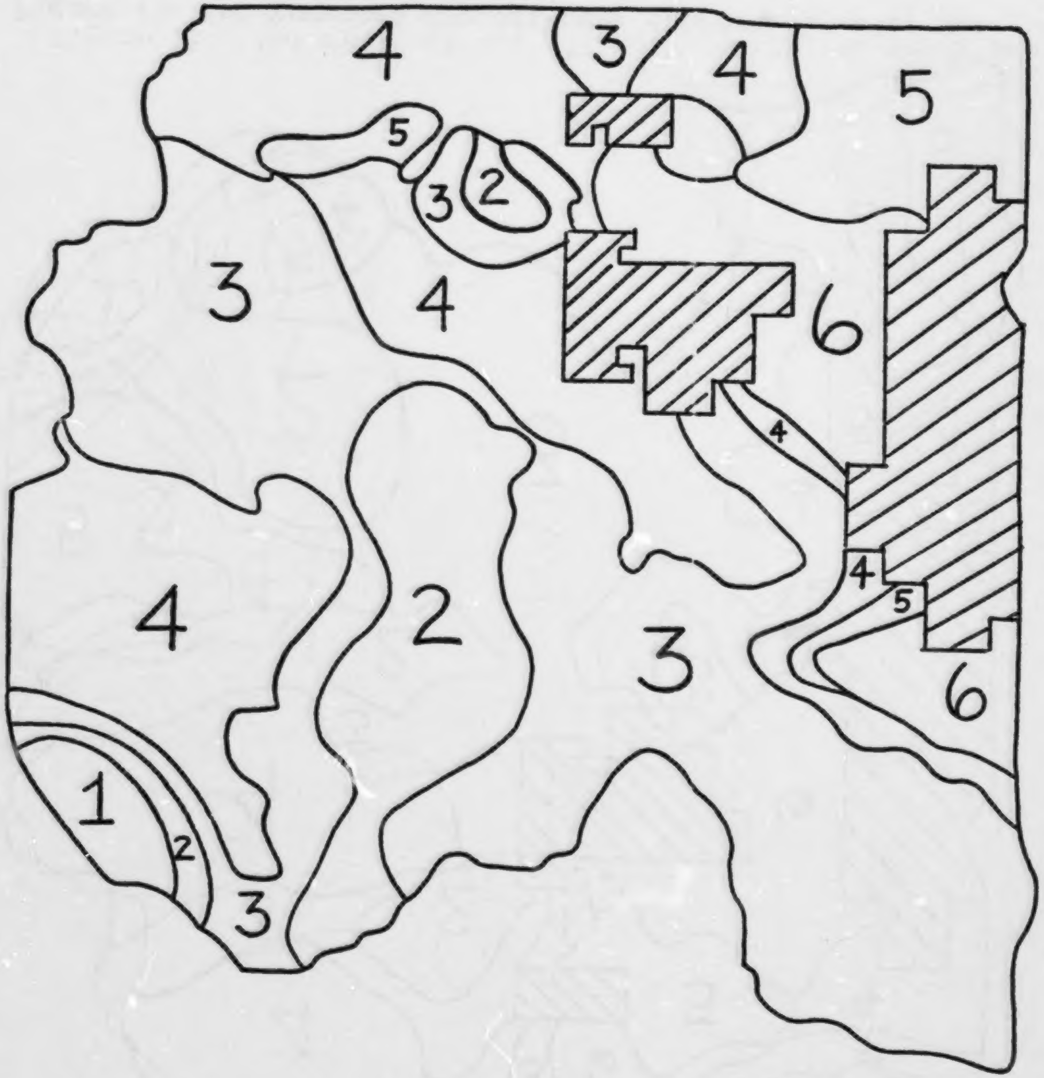
AREA	REVENUES MINUS OFF-PEAK COSTS COMMERCIAL
1	-.11 to -.06
2	-.06 to -.01
3	-.01 to .03
4	.03 to .06
5	.06 to .10
6	.10 to .14

Figure 23. Net revenues for off-peak commercial water use.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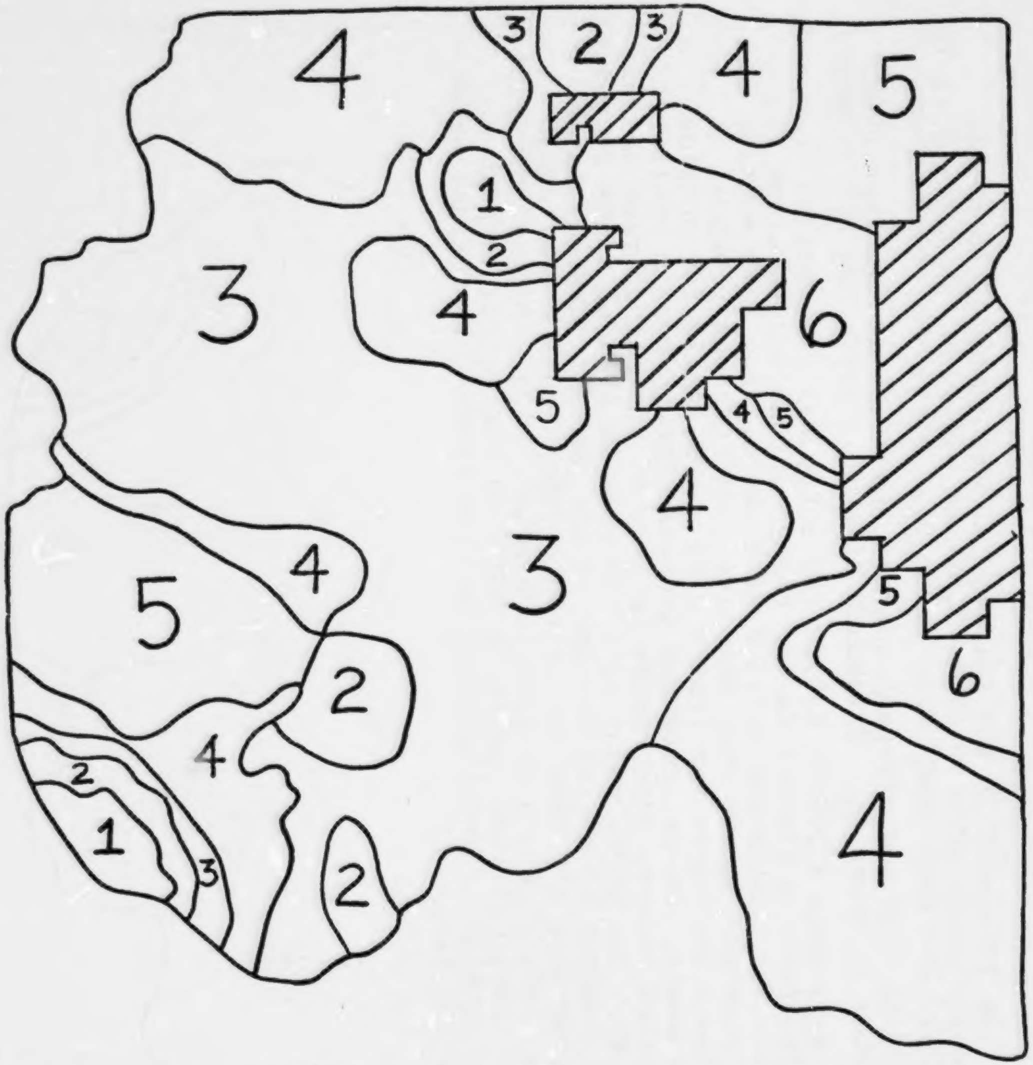
AREA	REVENUES MINUS PEAK COSTS INDUSTRIAL
1	-.11 to -.07
2	-.07 to -.04
3	-.04 to -.01
4	-.01 to .01
5	.01 to .04
6	.04 to .06

Figure 24. Net revenues for peak industrial water use.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AREA	REVENUES MINUS OFF-PEAK COSTS INDUSTRIAL
1	-.14 to -.10
2	-.10 to -.06
3	-.06 to -.03
4	-.03 to .01
5	.01 to .04
6	.04 to .07

Figure 25. Net revenues for off-peak industrial water use.

The general implication of these findings is that residences are subsidizing commercial and industrial uses of water, as residential customers showed virtually no cases of costs exceeding revenues, but this situation does occur for commercial and industrial users. Tables 15, 16 and 17 present detailed information on this point for the two water main routes presented earlier, C_1 and C_3.

One final piece of information on the spatial variation in net revenues is shown in Tables 18 and 19. Specific residential customers with a 5/8" meter were selected along routes C_1 and C_3, and calculations of total revenue and total costs were made for each, based on the customers actual water use, for both peak and off-peak periods.

As indicated in the tables, the magnitude of these net revenues range from -1.67 to 3.54 per off-peak quarter and -1.70 to 5.00 per peak quarter on route C_1. Also, they range from -1.52 to 3.26 per off-peak quarter and -1.76 to 2.50 per peak quarter on route C_3. Extending this to a year, the net revenues may vary from $7.00 to $20.00 for a typical residential customer. An interesting element is the change in the values along the routes for inside and outside city users. For both routes, the net revenues become more negative (cost exceeds revenue) as distance increases for inside city users, while for outside city users, the net revenues decrease though remain positive. As noted before, this occurs because of the higher rate in the county. The major point of these results is that costs increase with respect to distance. Use of the present quasi-distance pricing does decrease the possible subsidization that could occur from a return to a uniform zonal price. But, significant subsidizations still existing could be diminished through a redefinition of pricing zones to more accurately reflect water supply costs.

TABLE 18. RESIDENTIAL WATER USERS ROUTE C_1

			Quantity(CCF)		Total Revenue		Total Cost		Net Revenues	
Customer	Rate	Distance	Off-Peak	Peak	Off-Peak	Peak	Off-Peak	Peak	Off-Peak	Peak
1	Inside	3.85	21	22	$4.70	$4.90	$5.67	$5.93	$-.97	$-1.03
2	Inside	3.92	24	25	5.30	5.50	6.03	6.22	-.73	- .72
3	Inside	4.59	31	23	6.70	5.10	6.70	6.04	0.0	- .94
4	Inside	5.60	23	24	5.10	5.30	6.26	6.40	-1.16	-1.10
5	Inside	6.92	18	20	4.50	4.50	5.58	5.84	-1.08	-1.34
6	Inside	8.24	24	23	5.30	5.10	6.97	6.80	-1.67	-1.70
7	Out	9.77	17	16	9.00	9.00	5.46	5.41	3.54	3.59
8	Out	10.91	18	29	9.00	12.15	5.73	7.15	3.27	5.00
9	Out	13.85	20	22	9.00	9.70	6.26	6.60	2.74	3.10
10	Out	14.46	17	18	9.00	9.00	5.72	6.06	3.28	2.94
11	Out	17.38	20	18	9.00	9.00	9.41	8.62	-.41	.38
12	Out	18.02	16	16	9.00	9.00	8.79	8.18	.21	.82

TABLE 19. RESIDENTIAL USERS ROUTE C_3

			Quantity(CCF)		Total Revenue		Total Cost		Net Revenues	
Customer	Rate	Distance	Off-Peak	Peak	Off-Peak	Peak	Off-Peak	Peak	Off-Peak	Peak
1	Inside	5.70	26	34	$5.70	$7.30	$6.34	$7.20	$-.64	$ .10
2	Inside	8.01	16	18	4.50	4.50	5.45	5.72	-.95	-1.22
3	Inside	9.03	17	20	4.50	4.50	5.64	6.01	-1.14	-1.51
4	Inside	10.26	22	14	4.90	4.50	6.16	5.26	-1.26	- .76
5	Inside	10.99	25	20	5.50	4.50	7.02	6.26	-1.52	-1.76
6	Inside	12.86	17	25	4.50	5.50	5.71	6.67	-1.21	-1.17
7	Inside	13.45	19	27	4.50	5.90	5.94	6.92	-1.44	-1.02
8	Out	14.75	22	20	9.70	9.00	6.44	6.50	3.26	2.50
9	Out	15.65	19	21	9.00	9.35	6.89	7.12	2.11	2.23
10	Out	19.58	25	27	10.75	11.45	9.14	8.96	1.61	2.49
11	Out	20.13	13	22	9.00	9.70	6.44	8.14	2.56	1.56
12	Out	20.63	18	23	9.00	10.05	7.56	8.25	1.44	1.80

SECTION VI

INTRODUCTION TO PLUMBING PERMITS AND WATER USE

INTRODUCTION

Planning is a problem for any unit of government and is especially important for those activities characterized by capital intensive facilities, such as water supply. The long design and construction periods involved (up to 15 to 20 years) make it imperative to plan much in advance if potential users will find water available at a time and place where they are willing to pay for it.

In the case of water supply systems, the planning problem is to anticipate these three characteristics of development: its geographic direction, its pace and its intensity. Typically information of population movement and highway development is coupled with the water system planner's experience and professional intuition, and these serve as the principal elements of the planning process. The process ranges from the relatively formalized and detailed engineering studies to informal, intuitive or "seat of the pants" plans. The gathering of historical data is a usual part of making predictions, and since the development of a specialized data base as an input into water system planning and analysis is usually an expensive undertaking, it has been suggested that building permit data be utilized for this purpose. The apparent benefit to water system planning from employing such information lies in the fact that it is already being gathered on a continuous basis, and thus should be obtainable at a relatively low incremental cost.

However, while data on plumbing permits are gathered on a continuous basis, they are not gathered for water supply purposes, and thus are not likely to be immediately suitable for water system analysis. This was, indeed, one of the findings.

The question then is whether there is sufficient potentially significant information in the data base to make it worthwhile to modify it and/or supplement it in order to serve as a guide for water system development. The suitability of these data for this purpose would in large measure depend on the existence of sufficient lead time between the date of permit application and the date of first water use in order to acquire and factor the data into the planning process, and to carry out the necessary construction to meet the predicted future demand.

For this purpose, two types of empirical analyses were conducted in this study:

1. A simple analysis of the historical lags which have existed in a recent period (1969-1974) between plumbing permits (PP) applications and the date of initial water use. The statistics of the sample mean ($\bar{x}$), standard deviation (s) and coefficient of variation ($\bar{x}/s$) are presented as measures for these lags.

2. An attempt to estimate a lagged relationship between system wide water use and PP, where other causal variables are held constant. This work was inconclusive, as the variables of interest were not statistically significant while the hypothesis examined (that there exists a causal relationship between system wide water use and PP) may in fact be unsupported, the fact that the sample was drawn from a community which has experienced little or no growth suggests that the data base does not provide a good test of the hypothesis. Also, the original scope of the research (with attendant resources) precluded a further examination of whatever econometric problems were implicit in the techniques chosen to uncover the lags. We can say if there in fact exists a significant relationship, it is not so strong or obvious as to be insensitive to various estimation techniques.

The objectives of the research reported here then are:

1. To estimate the time lags which exist between the date of PP application and first water use at that address.

2. To test the hypothesis that these lags have a measureable impact on system wide water use when other variables are held constant.

SECTION VII

METHODOLOGY, EMPIRICAL RESULTS AND RECOMMENDATIONS

GENERAL PURPOSE

This chapter presents brief descriptions of the empirical methodologies employed for data collection and estimation of relationships.

The Data Base

The data base was drawn from three basic sources: (1) the City of Cincinnati building and plumbing permit applications and permits, (2) the Cincinnati Water Works, and (3) the Census. The period chosen for analysis was 1969 to 1974, and the data gathered on a quarterly basis.

The City of Cincinnati, exclusive of the surrounding suburbs and unincorporated county areas, was chosen for analysis for a variety of reasons, principal among which are (a) the lack of good and/or accessible record keeping outside the city and (b) the differences among permit systems, such that comparability is low among them.

The period of 1969-1974 was chosen because 1969 represented the first year in which water consumption records were sufficiently organized to be retrievable within the resource constraints of this project. As water meters are read quarterly only, this became the basic unit of data, and consequently the number of permits also were aggregated to a quarterly basis.

Analytical Methodologies

As indicated earlier, there are two principal empirical questions investigated in this report--(1) estimation of the lag (in days) that exists between the first recorded data for a building permit applicator (or plumbing permit) and the date of first use and also continuous use of water at the observed address; (2) estimation of the impact of building permits on system wide water use for the observation period. For the first, question, the lags were estimated by (a) drawing a random and stratified sample (22 data points per quarter) for the time period 1969-1974, (b) finding the date of building and plumbing permit application, (c) matching the address on the building permit with the water consumption account, (d) estimating the dates of first and continuous water use, and (c) calculating the days lapsed between the dates. The statistics for these computations appear later in this chapter.

The second question requires more complex methods in order to investigate it. The objective is to estimate and test the lagged impact of PP on system water use, holding constant other variables which affect water use. These estimates would be potentially useful as additional information regarding the capacities of the various acquisition, treatment and distribution systems by providing measures of the rate at which system and sub-system capacities are being approached.

The estimation of lags between variables is done fairly routinely in economics, especially where there is a need to measure the effects of changes in fiscal and monetary policy variables such as taxes, deficits, money supply, etc.

It was hypothesized that the impact on water use as earlier reflected by PP would be distributed over several time periods, instead of being concentrated in just one or two periods. As the basic unit of time chosen for analysis in this study is the quarter, it was hypothesized that the dates of initial water use associated with a specific period in which PP were applied for would first rise, reach a peak, and then taper off over time, as in Figure 26.

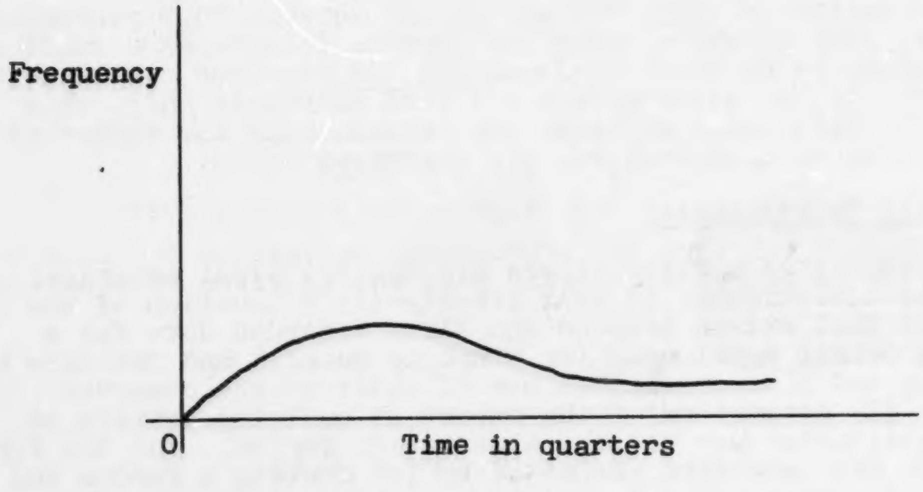

Figure 26. Distribution of initial water use.

The distribution in fact follows this form for Cincinnati. In terms of the impact on system water use, the weight to be attributed to each subsequent time period in terms of impact on water use will also decline. That is, the farther back one goes in time prior to the time period in which water use is measured, the less important will be the PP applied for in prior periods, since their peak impacts will become increasingly likely to have past. This concept is illustrated in Figure 27 where i is the time period, w_i is the weight:

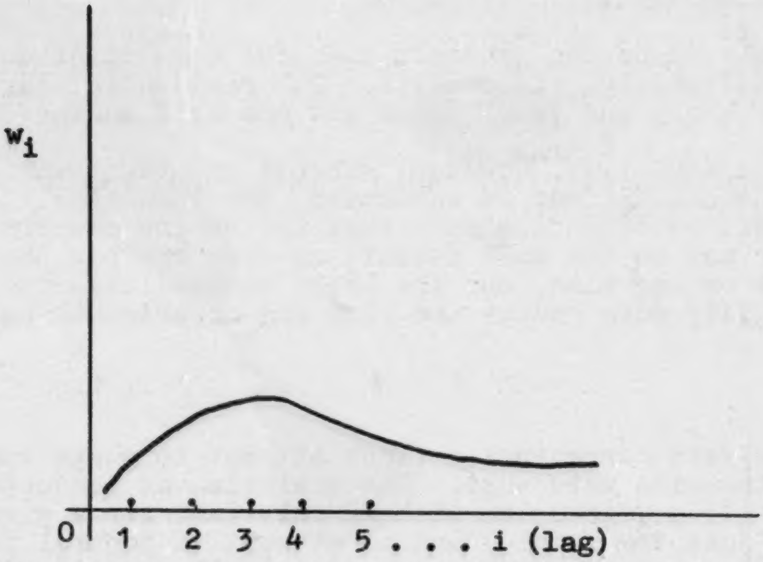

Figure 27. Declining weights for plumbing permits.

The functional form for statistical estimation for such a relationship is termed the Pascal Lag, and is given in equation (1)

$$Y_t = \alpha + \beta\,(w_0 X_t + w_1 X_{t-1} + w_2 X_{t-2} + \ldots) + \epsilon_t \tag{1}$$

in which the weights are estimated as:

$$w_i = (i + r - 1)!/i\,!\,(r - 1)!\,(1 - \lambda^{r}\lambda^{i})$$

where r is an integer to be chosen, and λ is estimated from the data.*

In the analysis undertaken in this study, other variables included in the regression equation were precipitation, price of water, family income, population, and temperature. Exact variable definitions are given below.

Empirical Findings

Simple Lags. This empirical analysis was conducted for the three basic user classifications examined in this study: residential, commercial and industrial. The analysis was conducted for new construction only, and does not apply to old construction in which some form of plumbing replacement, modification or addition took place. In Cincinnati, the preponderance of the permits were for the classification of old buildings. The sampling procedure yielded 250 observations on new residences, 53 on new commercial establishments, and 8 on new industrial plants. The findings are summarized in Table 20.

This table shows the greatest lags for commercial use, the industrial, and lastly, residential. The residential lag average 1.2 years, or about one year, three and one half months.

The commercial lags, however, exhibit the least variability, as seen by the coefficient of variation, and industrial lags, the most. This evidence suggests that the PP for commercial uses of water may be the most useful, as they exhibit the greatest lead or lag time, and the least variability--the reduced variability does reduce the risk and uncertainty associated with them.

Pascal Lags

This analysis represents a first attempt to guage the impact of PP on system-wide water use. The analysis was conducted in two stages: (1) a regression with PP only (all for a given quarter, not just the sample) and no attempt to control for other exogenous influences on water use, and (2) all permits with exogenous variables included. The regressions reported are not the function in (1), but rather the relationship using instrumental variables. Equation (1) has not been derived due to the inconclusive nature of the results. Also, the data was not scaled to dimension it to λ.

The results in Table 21 are for PP only, and do not support the (simplistic) hypothesis that PP alone have an impact on water

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*For a full discussion of the estimation technique, see Jan Kmenta, Elements of Econometrics, MacMillan, 1971, pp. 487-491.

TABLE 20. LAG TIME IN DAYS BY USER GROUP.

	(1) Mean	(2) 95% Confidence Limits	(3) Coefficient of Variation
Residential			
Initial Water Use	469.332	$431.912 < \mu < 506.75$	1.55
Continuous Use	476.552	$438.746 < \mu < 514.358$	1.56
Commercial			
Initial Water Use	543.962	$434.619 < \mu < 653.305$	1.37
Continuous Use	547.453	$438.449 < \mu < 656.457$	1.38
Industrial			
Initial Water Use	486.875	$310.316 < \mu < 663.434$	2.25
Continuous Use	490.250	$314.260 < \mu < 666.240$	2.27
Total			
Initial Water Use	482.501	$447.085 < \mu < 517.917$	1.51
Continuous Use	488.987	$453.349 < \mu < 524.618$	1.52

use. There are no significant values for the coefficients, or for the R^2's as shown by the F statistic.

The objective of the analysis of these lags with other exogenous variables was attempted, but it was not possible to carry out the analysis to such a point so as to say that an estimable lag does or does not exist in the experience of the Cincinnati system studied. It was desired to control for such influences as precipitation, price of water, income, population and temperature. Of these variables, the preliminary analysis showed that only temperature explain a statistically significant amount of the variance in water use. PP showed no effect.

In sum, with the data base that was selected for use in this study, it proved possible to estimate only the simple lags (days lapsed) between the date of plumbing permit application and the dates of first and continuous water uses. Attempts to hold constant other exogenous influences on water use and to estimate a weighted distribution of lags was not successful. This lack of success was probably due as much to the presence of greater intractability of the procedure that was anticipated as to the fact that the study area did not exhibit enough growth for PP to have any demonstrable impact on water use. Application of the procedure to a more rapidly growing area might prove successful.

TABLE 21. TOTAL WATER CONSUMPTION AND PLUMBING PERMITS: ANALYSIS OF PASCAL LAGS

		λ				
		0.1	0.2	0.3	0.4	0.5
Constant		8266519.39862	7272677.31940	6278835.40407	5284992.59275	4291150.16468
X_1	B_1	1831.86822	1565.57693	1299.28356	1032.99567	766.70123
	t	0.4011	0.3443	0.2837	0.2215	0.1599
	$Beta_1$	0.12128	0.10422	0.08600	0.06725	0.04861
X_2	B_2	1081.84735	1231.92541	1382.00527	1532.08221	1682.16447
	t	0.2422	0.2770	0.3086	0.3360	0.3588
	$Beta_2$	0.07324	0.08386	0.09354	0.10199	0.10906
	R^2	0.03226	0.02989	0.02718	0.02434	0.02153
	F	0.33334	0.30807	0.27942	0.24942	0.22006

		λ				
		0.6	0.7	0.8	0.9	1.0
Constant		3297307.73632	2303464.92500	1309622.98855	315780.74059	-678062.52825
X_1	B_1	500.40983	234.12194	-32.17137	-298.46323	-564.75475
	t	0.1007	0.0451	0.0059	0.0522	0.0937
	$Beta_1$	0.03064	0.01376	-0.00180	-0.01593	-0.02862

		0.6	0.7	0.8	0.9	1.0
X_2	B_2	1832.24365	1982.32059	2132.40056	2282.47985	2432.56087
	t	0.3769	0.3908	0.4010	0.4080	0.4126
	$Beta_2$	0.11473	0.11910	0.12232	0.12458	0.12607
	R^2	0.01893	0.01662	0.01466	0.01305	0.01176
	F	0.19292	0.16903	0.14881	0.13224	0.11902

Notes:

1. Y = Weighted change in water use from period to period, i.e. $Y_t^* = Y_t - \lambda Y_{t-1}$
2. X_1 = PP issued in previous period (t-1)
3. X_2 = PP issued in current period (t)
4. 23 periods were examined (n = 23)

APPENDIX A

SUPPLEMENT TO SECTION IV, PART A

The relationship of static, friction, pressure, and velocity elements to head was established in Bernoulli's equation for head-loss. Briefly, total head, H, in feet, can be estimated from:

(A-1) $H = PR_k \times \rho + Z_{ikr} + V^2/2g + H_L$ represents friction loss as calculated by the Hazen-Williams or Darcy-Weisbach formulae.[a]

S_a, the static head per foot of pipe, is formulated as: $S_a = Z_{ikr}/L_{jkr}$. Pressure and velocity head per foot of pipe, S_p, equals: $S_p = (PR_k \times \rho + V^2/2g)/L_{jkr}$. Since, $V = Q_{kr}/(\pi/4 \times D^2_{jkr})$, $V^2 = 16Q^2_{kr}/\ \pi^2 D^4_{jkr}$.

Therefore,

(A-2) $S_p = (PR_k \times \rho + 8Q_{kr}{}^2/\pi^2 g D^4_{jkr})/L_{jkr}$. But, Q_{kr} is measured in cu. ft. per sec. To obtain cu. ft. per day, multiply by 6.032×10^4 sec./day.

As a result,

(A-3) $S_p = (PRk \times \rho + (4.8256 \times 10^5\ Qk^2r)/(\pi^2 g D^4_{jkr}))/L_{jkr}$. Finally, friction head, H_L, may be added or defined in the Hazen-Williams equation.[b]

(A-4) $H_L = (4.72688)L_{jkr} \times Q_{kr}^{1.8518} \times C^{-1.8518} \times D_{jkr}^{-4.87}.^{3}$

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[a] The Hazen-Williams and Darcy-Weisbach equations can be found in any standard engineering text on water supply transmission.

[b] Since the study area for this project relies on the usage of the Hazen-Williams equation, that formula will be used.

(A-5) $S_f = H_L/L_{jkr} = (4.72688)\ Q_{kr}^{1.8518} \times C^{-1.8518} \times D_{jkr}^{-4.87}$.

Note that Q_{kr} here is also measured in cubic feet per second. Therefore, after multiplying by 6.032×10^4 sec./day, $S_f = (2.85125 \times 10^5)\ Q_{kr}^{1.8518} \times C^{-1.8518} \times D_{jkr}^{-4.87}$. Combining terms, $S_a + S_f + S_p$ can be derived.

(A-6) $$S_a + S_f + S_p = Z_{ikr}/L_{jkr} + (PR_k \times \rho + (4.8256 \times 10^5 Q_{kr}^2)/(\pi^2 g D_{jkr}^4))/L_{jkr} + (2.85125 \times 10^5)\ Q_{kr}^{1.8518} \times C^{-1.8518} \times D_{jkr}^{-4.87}.$$

APPENDIX B

RESIDENTIAL WATER DEMAND: A LITERATURE REVIEW

GENERAL PURPOSES

This appendix will examine the research that has been conducted on the determinants of residential water consumption. The kinds of statistical methods that have been used to explain residential water use and the different variables that have been associated with these different analyses will be discussed.

The traditional way of estimating future water consumption is the requirements approach (Grima, 1973, p. 60), where a unit variable, such as the number of persons or number of service connections, was selected as the basis for estimating water demand. The amount of water that each was assumed to use was then multiplied by the total number present to determine the total amount of water consumed. Often, water use has been measured on a per capita basis, where population is correlated with water pumped (Larson and Hudson, 1951, p. 603). Such measures have included Hanson and Hudson's (1956, p. 1347) proposed formula for establishing water use based on the following:

$$\frac{\text{Water Sold to Residential Users}}{\text{(No. of Services) (No. of Persons per Service)}}$$

Sometimes the number of homes was used as the measure of water demand, but then it was discovered that the number of homes did not necessarily give an adequate picture of the total amount of water consumed, since two areas with the same number of homes could have very different rates of water consumption.

It became apparent that water consumption varied from place to place not only because of the number of persons or homes present, but also because of other factors. Certain economic factors were identified as being influential in explaining area differences in water use by the use of a variety of statistical techniques. In 1939, Pond showed that per capita domestic water consumption varied between residential areas containing different housing types. Graphical comparisons were employed by Larson and Hudson in 1951 to discover that, instead of daily per capita water consumption being correlated with the population of Illinois communities, it was correlated with disposable income. Least squares estimates were next introduced into analysis. Wolff (1957, p. 230) used least squares estimates to discover the correlation between the percentage ratio of maximum day consumption to average day consumption and the population of the city. Fourt (1958) employed multiple correlation to discover the influence of different social, climatic, and economic variables on per capita residential water use. Both cross-sectional and time series regressions were used to derive equations based on comparisons of residential areas over space and over time. Recently Saunders (1970) used principal components analysis to determine what social and economic variables are similar in their variation between different communities and across the service area of the Louisville water works.

There are many different variables that affect residential water consumption; some of these can be identified by household surveys, such as garden watering, and the length of family holidays (Grima, 1972, p. 79). Still others are difficult to identify, such as household plumbing leaks, and therefore, it is possible that large errors will be present in any estimating equation of water consumption derived. Instead of adding more variables to the equation to increase the amount of variation explained, it is more important to select the variables that are most significant or are applicable to policy making.

Various social and economic variables have been mentioned in the literature as being significant in explaining variation in water demand. These variables are roughly divided into five groups: climatic variables, variables that measure the ability to consume water, variables that identify the presence of water consuming devices, measures of population density, and determinants of the price of water.

The Influence of Climate

Climate's main effect on residential water consumption is on water used outside of the home. The influence of climate on water use varies in intensity with the different seasons. Water use tends to peak during the summer when water is used for a variety of activities related to the warm weather, including lawn-watering, car-washing, filling swimming pools, and operating air conditioners (Fourt, 1958, p. 5). Of these uses, lawn sprinkling is probably the most important. The amount of water devoted to lawn sprinkling is in large part determined by both precipitation and temperature. Porges (1957, p. 204) reports that the per capita water demand between states varies directly with the annual precipitation. During periods of significant rainfall, water is stored in the grass roots zone and is enough to cover the loss of moisture to evapotranspiration. In contrast, during periods of little or no rainfall, sprinkling must be employed to counteract the withdrawal of moisture in lawns by evapotranspiration. Linaweaver, Geyer, and Wolff (1967, p. 273) reported that usually daily average lawn sprinkling is nearly equal to daily evapotranspiration. The nature of evapotranspiration is determined by the temperature, the amount of sunlight, wind velocity, type of soil, and humidity (Linaweaver, Geyer, and Wolff, 1967, p. 273).

The traditional way to determine what portion of residential water demand is used in lawn sprinkling is to find the difference in residential water use between a wet day and a dry day, and to assume that this difference is the amount of water devoted to lawn watering (Wolff, 1961, p. 1254). Howe and Linaweaver (1967) suggest a way of calculating the amount of water needed for a lawn or other area subject to irrigation that includes the effect of evapotranspiration. In its simple form, their equation is (1967, p. 21):

$$q_{s,s} = b \cdot (W_s - 0.6r_s)$$

where:

$q_{s,s}$ = the average summer sprinkling demand in gallons per dwelling unit per day;

b = area subject to irrigation by dwelling unit;

W_s = the summer potential evapotranspiration in inches;

r_s = summer rainfall in inches.

Howe and Linaweaver recognized that these physical requirements are also subject to the influence of the economic status of the residents, and the price of water. Therefore, they have amended the above equation to (1967, p. 21):

$$q_{s,s} = B_0 b^{B_1} (W_s - 0.6r_s)^{B_2} p_s{}^{B_3} v^{B_4} \cdot u$$

where:

p_s = the marginal commodity charge applicable to average summer total rates of use;

v = the value of the dwelling in thousands of dollars.

The differences in sprinkling demand from one area to another became apparent in their statistical analysis of summer sprinkling (Howe and Linaweaver, 1967, p. 28). They examined sprinkling demands in twenty-one residential areas in the United States, ten in the West and eleven in the East, where the accounts were metered and sewered. They discovered that the variables, irrigable area and climate, were not always significant explanatory variables as had been theorized. These equations included the following (1967, p. 28):

for metered and sewered connections in the West:

$$q_{s,s} = 3.053 - 0.703 \log p_s + 0.429 \log v \quad R^2 = .674$$

t-statistic[a] 2.19* 1.88*

for metered and sewered connections in the East:

$$q_{s,s} = -0.784 - 0.793 \log b + 2.93 \log (W_s - 0.6r_s)$$

t-statistic 3.65** 6.83**

$$-1.57 \log p_s + 1.45 \log v.$$

t-statistic 8.26** 4.74** $R^2 = .927$

The two climate variables appear only in the equation explaining sprinkling demand in the East.

Other research has produced mixed results when using climatic variables in regression equations of residential water use. Wong (1972, p. 38) included the effect of climate on water consumption by using the average summer temperature for each observation with a price variable, and an income variable. He found that this climatic variable was significant in explaining variations in per capita municipal water demand in metropolitan Chicago for the years 1951-1961 (1972, p. 40). Fourt (1958) measured the influence of climate in another manner. In the equation that he derived, he found that the number of days of rainfall in the summer months was significant in explaining water consumption in forty-four cities when used with the two variables: persons per meter, and price (1958, pp. 7-8).

In Young's (1973, p. 1070) work on identifying factors significant in determining water demand, he used the two climatic measures, temperature and evaporation. They were removed from his equation when he found that they were not significant or had a sign contrary to the one hypothesized. (1973, p. 1070).

The different aspects of climate, such as precipitation and temperature, can be most useful in explaining variations in residential water consumption in two types of situations; first, between cities of different climatic regions, and second, for any number of cities over a period of years. Since climate generally does not vary appreciably across the service area of a single water utility, it probably is of little use in explaining the spatial variations of water consumption in a city for a single year.

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[a] The level of significance for the t-statistic in these equations and those following is denoted by * for significance at the .95 percent confidence level and ** for significance at the .99 percent confidence level.

The Influence of the Cost of Water

A set of water utility practices as influential on water consumption as climate, and even more so at the micro level are those concerned with the price of water. These price variables include metering and rate schedules. Metering may be the most important of these in affecting water consumption. A water account is either metered, where the user is charged according to how much he consumes, or charged a flat rate regardless of how much water is consumed.

Metering can change water use trends and the shape of consumption peaks. It can lower per capita consumption and change the future trends of water use (Flack, 1967, p. 1341). The philosophy behind metering is not to restrict water consumption, but rather to prevent the waste of water (U.S., Congress, Senate, 1960, pp. 15-16). It is supposed to provide the incentive to repair water leaks in both domestic and municipal water equipment (Howe and Linaweaver, 1967, p. 14). Flack (1967) observed the effect that metering had on water use in Boulder, Colorado during the 1960's. Based on his experience, he suggests cities of similar size can expect about a thirty percent reduction in water demand after all accounts are metered (1967, p. 1343).

The metering of water accounts has its greatest influence on reducing the amount of water used in lawn sprinkling. Linaweaver, Geyer, and Wolff (1964, p. 1128) found that water demand in unmetered areas of small lots can nearly equal that in metered areas containing very large lots. Howe and Linaweaver (1967, p. 14) report the annual average rates of use per dwelling unit in eight flat rate areas to be 692 gallons per day, but only 458 gallons per day in ten metered areas. Their flat rate areas used 420 gallons, per day, per dwelling, on the average, for sprinkling compared to 186 gallons in the metered areas, but the average annual figures for household water use were 236 gallons, per day, per dwelling, in flat rate areas and 247 gallons in the metered areas (1967, p. 14). These results may mean that domestic water use is more price inelastic than water used for lawn sprinkling.

Hanke (1970) observed the effects that metering water accounts had on both in-house water use and lawn sprinkling in Boulder. He examined fourteen meter reading routes after water meters had been installed and found that sprinkling declined dramatically. In most cases, the water consumption dropped to levels below that required to maintain "the aesthetic quality of one's yard; its green appearance" (Hanke, 1970, pp. 1255-56). Domestic or in-house use of water dropped an average of thirty-six percent after metering (Hanke, 1970, p. 1258). He also discovered that the impact of the installation of meters on water use did not wear off as time went on. In most cases, the amount of sprinkling water used per capita continued to decrease, which implies that the price elasticity for water is increasing over time (1970, p. 1256). This decline in water use has occurred while incomes have increased, suggesting that the income elasticity is becoming more inelastic (Hanke, 1970, p. 1256).

The effect of metering varies between single homes and apartments. Metering may be more influential in limiting water use in areas where each home is individually metered in contrast to areas where there may be only one meter for many dwelling units. Apartment dwellers may not be directly metered, but they are still indirectly affected by metering through the rent they pay (Fourt, 1958, p. 3). But this is not a marginal charge since their rent does not account for variations in water use.

Water rate structures are usually dependent upon metering to help determine the cost of water to each consumer. The type of pricing structure employed can be useful in helping to avoid underuse and overbuilding of the system (Hanke and Davis, 1971, pp. 555-56). A wide range of different rate structures are used in the water utility industry. In communities where water accounts are not individually metered, a fixed charge or flat rate for water is used. Unfortunately, this leads to waste and excessive water consumption (Mann, 1970, p. 535). Increases in water rates in unmetered areas may not lead to reductions in water use, but rather can lead to increased demand "because the customer has no incentive to save water, as he is paying more, he is inclined to use more" (Flack, 1967, p. 1343).

When each account is metered, many different water rates can be employed. The simplest is a uniform rate where the customer is charged the same for each unit consumed, no matter how much he uses (Mann, 1970, p. 534). A variation of this rate system is where there is a minimum charge plus a per unit charge made on all water consumed (Afifi, 1961, p. 43). These types of rate structures ignore the possibility of cost variations in a utility providing different amounts of water (Mann, 1970, p. 535).

A second type of metered rates is block schedules. Under these rate schemes, the price per unit of water varies between different quantities of consumption. In general, block schedules are of a declining nature, where the cost of a unit of water declines in each successive block (Afifi, 1969, p. 42). Mann (1970, p. 535) criticizes this rate structure because it assumes costs decline with increased consumption, but not enough cost data exists to accept or reject this theory. The declining block rate may affect a water utility in numerous ways.

> For example, the declining block schedule, on one hand, may encourage water uses (sprinkling) which are key contributors to peak demands, with the result being a worsening of the utility's peak load problems. On the other hand, large commercial or industrial users, receiving water at a single outlet (while making contribution to system peaks) may be a prime example of declining supply costs with increased usage (Mann, 1970, p. 535).

Another variation on block rates is a two-part rate which is a combination of a declining block rate and a fixed demand charge (Mann, 1970, p. 535). This type of pricing system may suffer from the assumption that the demand charge is based on a consuming group's contribution to peak demands, where in reality, those users, whose contribution is biggest, may consume most of their water at off-peak periods, while smaller users may consume most of their water at peak user periods (Mann, 1970, p. 535).

Water rates should reflect the incremental costs incurred in providing additional facilities. This is an issue when comparing summer water use with winter water use. Since summer water consumption is so much greater than winter consumption, the cost of providing water increases. If rate structures do not vary seasonally, to take account of these costs, then investments in new equipment and facilities, to account for peak water demand periods, are "larger than economically justified" (Hanke and Davis, 1971, p. 556).

The problem of equity is further intensified when it is realized that summer customers are being subsidized in part by winter ones, since the winter consumer is paying in part for the additional plant capacity required by the summer users. In general, inner city consumers, with little or no lawns, are subsidizing the suburbanites with their large lawns and greater summer peak demands (Hanke and Davis, 1971, p. 556). There are pricing methods employed that are designed to overcome these problems. Seasonal pricing is used to help keep peak water demands under control and is useful in delaying capital investments to increase plant capacity (Hanke and Davis, 1971, p. 559). Higher outside city water rates are frequently used, though usually as a payment in place of municipal taxes or to provide an incentive for annexation, instead of covering higher outside city peak demand (Afifi, 1969, p. 45).

It may take more than special or seasonal water rates to limit sprinkling use. In Kansas City, Hatcher (1956, p. 374) found the ratio of maximum to average day lawn sprinkling to be seven or eight to one, or much greater than the ratio of 1.25

to 1 for domestic use. Howe and Linaweaver (1967, p. 29) point out that a higher price for water may provide the incentive to be more conservative in lawn sprinkling, but pricing alone does not provide an incentive to avoid those times of very high rates of water use. This is because the times available for watering lawns are largely set by considerations other than price.

In addition to the water rates and special charges already discussed, other charges have been employed by the water utility industry. These include annual assessments on the width of the customer's property, connection charges, and ad valorem taxes, which are levied to recover some or all of the costs of water utility operation and expansion (Linaweaver, Geyer, and Wolff, 1964, p. 1127). In some communities, sewer charges are based on the amount of water consumed and may have an indirect influence on water demand (Linaweaver, Geyer, and Wolff, 1964, p. 1127).

In the case of industry, some costs such as labor have been increasing faster than the price of water so that the cost of water has experienced a relative decline and water is substituted for labor in carrying off wastes (Seagraves, 1972, p. 476). This situation can also occur in the case of residential water use, where income and inflation can cause water charges to decrease in relation to other prices, resulting in increased water consumption (Young, 1973, p. 1072).

In statistical analyses, the price of water has been used to explain residential water consumption with varying degrees of success. Fourt (1958, p. 8) found that the price of water in dollars per 1000 cubic feet per month was significant in explaining the amount of water used per person per year when used with the two variables, number of days of rainfall in the summer months, and average number of residents per water meter. Wong (1972, pp. 38-39) used both cross-sectional and time series regression to analyze water consumption data from Chicago and its suburbs. He discovered that the price of water was a significant predictor of average per capita water demand per municipality. In his equations, he included the price variable with average summer temperature and average household income. Price was a significant explanatory variable in his cross-sectional analysis for cities of populations over 5,000. But in the time series regression of water consumption in Chicago, price was not significant because Chicago charged a flat rate for water (Wong, 1972, p. 39).

Grima (1972, p. 100) used three samples, one included in the second, and both contained in the third, to test a series of price-related variables and determine their individual effectiveness in establishing annual water use in gallons per day per dwelling unit. These variables were: the number of billing periods per year, the number of gallons per day allowed to each dwelling in the minimum bill, the size of the minimum bill, and the price of water in cents per 1000 gallons. In his results, two of these variables, the amount of water allowed with the minimum bill, and the number of billing periods per year, were not significant in explaining water use (1972, pp. 101-2, 105). The variable, price in cents per 1000 gallons, is a significant explanatory variable for accounts in only two of the sample areas (Grima, 1972, p. 105). The most significant price oriented variable was the fixed bill per period. It was significant in explaining water use in each of the samples (Grima, 1972, pp. 101-2, 105-6).

Gardner and Schick (1964) examined the effect that seven different climatological and income related variables had on water use in forty-three northern Utah communities. The final equation which they derived contained only the price of water and lot size as follows (1964, p. 13):

$$\text{Log } Y = 5.9504 - .7662 \log X_1 + .1506 \log X_4$$

$$\text{t-statistic} \qquad -11.70^{**} \qquad 2.15^{*} \qquad R^2 = .83$$

where:

Y = per capita daily water consumption;

X_1 = average price of water per 1000 gallons;

X_4 = per capita lot area.

Estimating the price elasticity of demand for water has become very important in studies of residential water use, since it is helpful in determining how a rate increase or how differences in water rates will affect the demand for water. Under former forecasting techniques, future water consumption was determined by estimating population and multiplying it by the current average per capita water consumption. This entirely ignores the influence that changes in the cost of water and subsequent changes in price have on demand, which must be estimated if accurate predictions are to be made (Hanke, 1970, p. 1254). Price elasticity can be defined as the percent change in quantity demanded compared with the percent change in price. The price elasticity is inelastic when percent changes in price are greater than percent changes in quantity demanded, and elastic when percent changes in price are less than percent changes in quantity demanded.

The estimates of price elasticity have varied considerably from study to study. In Illinois, Afifi (1969, p. 41) found the demand for water by residential customers to be highly inelastic. Young (1973, p. 1071) examined water data in Tucson using a time series analysis and estimated the price elasticity of water demand to be -.65 for the years 1946 to 1964, and -.41 for the years 1965 to 1971. This shift in the price elasticity could have been caused by many factors. It coincided with substantial price increase, and as the price of water increases, the nonessential uses will be curtailed and essential uses will become a larger share of the total demand. This will make the demand for water more price inelastic (Young, 1973, p. 1072). In Wong's (1972, p. 40) analysis, the price elasticity ranged from -.26 to -.82 in his cross-sectional analysis. In his time series analysis of water data, the price elasticity ranged from -.02 to -.28 (1972, p. 40). In northern Mississippi communities, the price elasticity varied from -.26 to -.45 (Primeaux and Hollman, 1974, p. 142). In Kansas communities, the price elasticity was found to be between -.66 and -1.24 (Gottlieb, 1963, p. 210). Finally, Gardner and Schick (1964, p. 13) calculated the price elasticity to be about -.77 in the communities which they examined in Utah.

The price elasticity of demand for water varies between domestic use and sprinkling use. Of the water consumed for residential purposes, the price elasticity for sprinkling water is greater than that for domestic demands (Howe and Linaweaver, 1967, pp. 27-28). Howe and Linaweaver found the price elasticity for domestic demands in metered and public sewered areas to be -.23 (1967, p. 27). In the same areas, the price elasticity for the demand of summer sprinkling water was -1.12 (1967, p. 25).

The influence of seasonal change on price elasticity has been explored by Grima (1972). He developed three equations of residential water consumption, one for average annual consumption, one for average summer use, and one for average winter use (1972, p. 80). The price elasticity of demand for the entire year was -.93, but it was -1.07 for the summer period, and only -.75 for the winter period (Grima, 1972, p. 111).

These variations in the price elasticity may be due to a number of reasons, including the type of price variable used. For example, the price variable which Howe and Linaweaver (1967) employed was "the sum of water and sewer charges that vary with water use, evaluated at the block rate applicable to the average domestic use in each study area" (p. 19). In contrast, Gardner and Schick (1964, p. 14) used the average price per 1000 gallons of water. Flack (1967) may have discovered a series of reasons for differences in the price elasticity, by observing Colorado Springs, Colorado, where "it was found that despite substantial price increases, the effect on demand was obscured by larger lawn areas and consequent larger sprinkler loads in new housing developments, water use restrictions, and year-to-year climatologic variations" (pp. 1342-43).

Using information on expected rate increases to forecast future water demand may not provide very accurate predictions for a number of reasons. First, the range in the price of water is not great enough between urban areas to provide knowledge on the price elasticity of water at prices significantly greater than currently charged (Saunders, 1969, p. 30). Second, the cost of supplying more water to urban areas may increase at different rates than in the past (Saunders, 1969, p. 30). Third, building forecasting models can be hampered by not only trying to estimate when future rate increases will occur, but also by the change that new types of rate structures will be employed (Hittman Associates, Inc., 1969, p. IV-12).

Measures of the Ability to Consume Water

Residential water consumption depends in large part upon the ability to consume water. Two measures frequently used in this context are the income of the consumer and the value of his home. The effect of income has long been recognized as being important in determining how much water consumers will purchase. In 1939, Pond (p. 2008) reported that per capita water consumption was greater in more prosperous neighborhoods. Income was one of the first variables to be selected in place of population in explaining residential water consumption (Larson and Hudson, 1951, p. 603). In 1951, Larson and Hudson (p. 606) found the greatest water consumption per person to be occurring in communities in Illinois where incomes were greatest. It was theorized in the 1950's (Hanson and Hudson, 1956, p. 1355) that increases in income would correspond to increased water consumption, because the higher the income of the consumer, the greater the likelihood he would purchase more water-using appliances. Increasing incomes not only means that more water-using appliances are used, like washing machines and dishwashers, but also that leisure time and water-related recreation time is increasing (Sewell and Bower, 1968, p. 21).

To test the influence of income, it is usually difficult to obtain data on per capita income. In these situations, proxy variables are used.

> Most studies tend to rely on the use of median family income given by the census of population. Few use average household income, which may be obtainable from sales management or market surveys. Where the later index is unavailable, proxy variables namely, assessed property value, number of water-using appliances (such as dishwashers and automatic washers) in a household, size of lot, number and type of automobile owned by family, are used (Wong, 1972, p. 36).

As an example of a proxy variable used in place of income, Young (1973, p. 1069) employed retail sales per person per time period in his study of water use in Tucson.

Income variables have been used frequently in studies of water consumption and have been found to be important explanatory variables. In Saunders' (1969, p. 20) principal components analysis of different variables influencing water use in ninety-three American cities, he discovered that those that measured urban area size and income have the most influence on water usage. But, Whitford (1972, p. 830) complained that Saunders did not separate residential water usage from the total consumed, and also failed to include many other important variables in his analysis, including average lot size and climate.

Wong (1972) included the effect of income in his analysis of water consumption in the Chicago area in the form of the average household income in each municipality for each year under examination. In time series analysis, income was significant in explaining only Chicago's average per capita water demand and not the water demand of the other cities included in his analysis (1972, pp. 39-40). In his cross-sectional analysis, the income variable was significant in explaining water consumption in only those cities with populations of over 10,000 persons (1972, pp. 39-41). Unfortunately, the R^2's for the equations where income was significant in the cross-sectional analysis were rather small, suggesting that the effect of other variables must be explored (Wong, 1972, p. 41).

Headley (1963) examined median family income and its effect on water consumption in gallons per capita per day in fourteen cities in the San Francisco Bay area. He determined the correlation between these two variables for both 1950 and 1959, and derived the following equations (1963, p. 444):

for 1950: $X_0 = -30.24 + 2.16X_1 \qquad R^2 = .81$

t-statistic 7.33**

for 1959: $X_0 = -18.77 + 1.27X_1 \qquad R^2 = .80$

t-statistic 6.86**

where:

X_0 = gallons per person per day;

X_1 = annual median family income in hundreds of dollars.

A time series analysis of residential water use for each of the fourteen cities was done for the ten years between 1950 and 1959 (Headley, 1963). The income variable explained a smaller amount of the variance in the individual time series analyses than in the one cross-sectional analysis (Headley, 1963, pp. 444-46).

An income variable was included in the study of sixteen New Mexico communities done by Berry and Bonem (1974, p. 1239). They examined the influence of four variables on average per capita water consumption. These variables were: the price of water, the population of each municipality, the sprinkling requirements, and the per capita personal income (1974, p. 1239). Their results showed only income to be significant in explaining water demand (1974, p. 1240). Their final equation was (1974, p. 1240):

$$g = 31.7 + 0.051y$$

t-statistic 3.00** $R^2 = .39$

where:

g = water use in gallons per person per day;

y = annual per capita income.

Unfortunately, the coefficient of determination for this equation was only .39 (Berry and Bonem, 1974, p. 1240).

A variable measuring income has proven to be of little importance in at least one study of municipal water demand. Gardner and Schick (1964, pp. 11-12) found that per capita median income was not significant in explaining per capita water use and that its regression coefficient had the wrong sign. They (1964, pp. 16-17) explained these results as being caused in large part by two problems. First, the results may be indicative of only the study area and may have been different if the range in median incomes had been greater. Second, since their study compared differences in water consumption between communities, it obscured variations within communities, possibly minimizing the influence of income.

The income elasticity for water has been calculated by many researchers and is useful in understanding how changes in income will affect the demand for water. In California, Headley (1963, p. 444) found the income elasticity in his cross-sectional analysis of fourteen communities to be 1.49 in 1950 and 1.24 in 1959. The income elasticities for each individual community studied in a time series analysis ranged from .00136 to .4035, with a simple average of about .25 for all the communities (1963, p. 446). In comparing the income elasticities derived from the two analyses, he says (1963, p. 446):

> In view of the historical information we have, showing the increases in gallons per capita per day of residential water purchases over time from 1950 through 1959, the elasticities estimated from the time series analysis seem to be more reasonable.

The higher elasticities in the cross-sectional analysis may be due to income being a proxy for other variables such as the number of bathrooms per house, the presence of washing machines, or the average lot size, which may vary more between the cities included in this study than within them (Headley, 1963, p. 448).

Wong's (1972) analysis was similar to Headley's in that the income elasticities were greater in the cross-sectional analysis than in the time series analysis. In Wong's (1972, p. 40) cross-sectional analysis, the price elasticity ranged from 1.03 to .58, while in the time series analysis, the price elasticity for Chicago was .20 and .26 for the other communities.

Howe and Linaweaver (1967) calculated the income elasticities for both sprinkling and domestic water in a cross-sectional analysis, where they used property value as a surrogate for income. They (1967, p. 27) calculated the income elasticity for domestic water to be about .35 in sewered areas. The income elasticities for sprinkling water were .4 in metered western areas and 1.5 in the metered eastern areas (Howe and Linaweaver, 1967, p. 28).

A second variable indicative of the ability to consume water is the value of the consumer's home. The value of the home is assumed to be positively correlated with the size of the lawn and the number of water-using appliances in the dwelling. Howe and Linaweaver (1967, p. 20) suggest that the value of the home "determines an approximate per capita usage through water complementary appliances, baths, etc."

Howe and Linaweaver (1967) discovered that the value of the home in thousands of dollars was a significant variable in explaining both average annual domestic and average summer sprinkling water consumption. They derived the following equation to explain domestic water consumption in twenty-one metered and public sewered areas, and thirteen flat rate and public sewered areas containing apartments (1967, p. 24):

metered and public sewered areas:

$$q_{a,d} = 206 + 3.47v - 1.30p_w$$

t-statistic

flat rate and sewered area with apartments:

$$q_{a,d} = 28.9 + 4.39v + 33.6p$$

t-statistic 7.87** 3.97**

where:

$q_{a,d}$ = average annual water demand for domestic use in gallons per dwelling per day;

v = value of the home in thousands of dollars;

p_w = water and sewer charges according to average domestic use.

In the case of water used for summer sprinkling in twenty-one metered and public sewered areas and eight areas with flat rates and public sewers, Howe and Linaweaver (1967, p. 25) derived the following two formulas:

metered and public sewered areas:

$$q_{s,s} = 1.09 + 2.07 \text{ Log } (w_s - 0.6r_s) - 1.12 \log ps$$

t-statistic 4.59** 5.00**

$$+ .662 \text{ Log } v$$

t-statistic 3.06**

flat rate areas with public sewers:

$$q_{s,s} = 2.00 + .783 \text{ Log } v$$

t-statistic 3.24** $R^2 = .635$

where:

$q_{s,s}$ = average summer sprinkling demand;

p_s = marginal commodity charge on average summer total rates of consumption;

w_s = summer potential evapotranspiration in inches;

r_s = summer rainfall in inches.

Linaweaver, Geyer, and Wolff (1967, p. 273) have calculated a correlation coefficient of .76 between the value of the home and residential water use based on data from thirty-one residential areas. Their equation is (1967, p. 273):

$$\overline{Q}_d/a = 157 + 3.46V \qquad R^2 = .58;$$

where:

$\overline{Q}_d/a$ = average domestic water use in gallons per day for each dwelling;

V = average value of the dwelling in thousands of dollars.

Grima (1972) used the assessed sales value of the dwelling unit in hundreds of dollars as a measure of housing value in his research. This measure of housing value appeared in all of his final equations, containing just significant variables, as follows (1972, p. 105):

average annual demand:

$$WU_a = 131.26 + 0.37V + 22.15Np - 2.14P - 0.16F$$

t-statistic 3.20** 7.22** -4.5* -2.56** $R^2 = .52$;

average summer demand:

$$WU_s = 152.28 + 0.41V + 26.15Np - 2.61P - 0.19F$$

t-statistic 3.51** 6.98** -4.5** -2.4** $R^2 = .50$;

average winter demand:

$$WU_w = 115.72 + 0.26V + 20.43Np - 1.74P - 0.13F$$

t-statistic 2.82** 6.9** -3.8** -2.07* $R^2 = .46$;

where:

WU_a = annual average water use in gallons per day per dwelling;

WU_s = summer average water use in gallons per day per dwelling;

WU_w = winter average water use in gallons per day per dwelling;

V = assessed sales value of the dwelling unit in the hundreds of dollars;

N_p = number of persons per residence;

P = price of residential water in cents per 1000 gallons;

F = the fixed bill for each billing period in cents.

The value of homes has not always proven to be important in determining water use. As with income, the value of homes did not prove to be a significant variable in Gardner and Schick's (1964) analysis of water use. They explain this result as being similar to the results of the income variable, where the analysis overlooked variations in home values within communities. (1964, p. 18). Also, they felt that in-house use of water may not vary significantly between homes of different value, since most homes, no matter what their value, have certain water-using appliances (1964, p. 18).

The Influence of Water-Using Appliances

The numbers and types of different water-using appliances, present in each household, form a third set of variables important in establishing residential water consumption. These appliances are related to the consumer's median income and the value of his home, since they are usually indicative of his economic status. Per capita residential water use should increase with their addition to the home (Wolff, 1957, p. 225). The amount of water they consume depends on the consumer's income level, the number of persons in the home, and the cost of water (Grima, 1972, p. 79).

> The rate of water use by each appliance (w_i) is dependent upon its technical efficiency. In the case of residential water use, this efficiency level is partly under the control of the user; care of use and the repair of water-using appliances (particularly the household plumbing system) are relevant to the magnitude of w_i. The rational consumer adjusts to the marginal price of water by using water more effectively (Grima, 1972, pp. 79-80).

The use of domestic water-using appliances is essentially different from lawn sprinkling in that it is not seasonal and therefore has different peaking characteristics; also. daily rates of domestic water use are generally the same in summer as in winter (Howe and Linaweaver, 1967, p. 17).

Water-using appliances generally fall into the following three groups: toilets and bathing facilities, home laundry and kitchen appliances, and air-conditioning equipment. Water used for bathroom equipment is a major source of in-house water demand. Water use per toilet flush varies from 3.2 to 8 gallons or more

(Howe and Vaughan, 1972, p. 118). Bathing is also very important; thirty percent of domestic water use is devoted to it and sixty percent of this is used in showers (Howe and Vaughan, 1972, p. 120).

There has been a tendency, in recent years, to increase the number of bathrooms in American homes. Seidel (1969, p. 490) found that in Ames, Iowa, the size of homes had increased over the previous ten to fifteen years and now many had additional bathroom facilities. In spite of the increase in the number of bathrooms, much of this is excess capacity that is used only rarely (Wolff, 1957, p. 1256).

Home laundry equipment and automatic dishwashers have, over the last few decades, become increasingly common in American homes. The percentage of total water consumed within a home for clothes-washing and dish-washing ranges between twenty and twenty-seven percent of the total (Howe and Vaughan, 1972, p. 119). The amount of water used by these appliances varies according to the amount of water they use in each operating cycle. Consumer Reports (August, 1969, p. 443) found that automatic home clothes-washers use between thirty-two and fifty-nine gallons of water for each eight pounds of load. In a study of water use in two homes in Louisville over a period of seven days, it was discovered that, on the average, the washing machine and dishwasher were used 0.7 and 0.8 times, respectively, per day (Anderson and Watson, 1967, p. 1235). Food disposers were used an average of 1.8 times per day in the same homes (Anderson and Watson, 1967, p. 1235).

Peak in-house water demands have been increasing because of the use of automatic appliances. It is now possible to have a number of them running at the same time (Heggie, 1961, p. 264). Household appliances can place a large demand upon a water utility, but this does not need to be the case, since available technology could reduce present domestic water use by thirty-two percent[a] (Howe and Vaughan, 1972, p. 121).

Sometimes incentives are employed to limit the use of water for domestic purposes. An example of this has been in regard to air-conditioning, which became a substantial problem to water utilities in the 1950's because their consumption of water nearly corresponded with the summer peak demands for water (Rynders, 1960, p. 1242). To solve this problem, two approaches were taken. First, in some communities, special demand charges or surcharges were enacted to control the amount of water used in air-conditioning (Afifi, 1969, p. 45). In the case of demand rates, the higher a customer's peak demand, the greater the charge (Rynders, 1960, p. 1239). A second way of controlling water use in air-conditioning was by ordinances. In the 1950's, Kansas City passed an ordinance requiring new air-conditioning units to be of the type that recirculated the condenser-cooling water (Hatcher, 1956, p. 374). The use of ordinances, instead of special charges, has been found in one study to be the most common method employed to control water consumption by air-conditioning equipment (Afifi, 1969, p. 45).

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[a] This could be accomplished through the use of shower heads with lower volumes of water flow, the installation of domestic water reuse systems, and the selection of the most water-conserving appliances available (Howe and Vaughan, 1972, pp. 118-21).

Air-conditioning's effect on water demand has declined in recent years due to increased water rates and the use of ordinances (Hatcher, 1965, p. 275). It has also experienced a decline because of the increased use of air-cooled units and the replacement of a number of smaller units in buildings with central water-conserving units (Committee Report, 1965, pp. 1456-57).

The Effect of Population and Housing Density

A fourth set of explanatory variables are related to population and density; these variables determine both the water demand per dwelling and per area. They include variables measuring different characteristics of the consumers, like population density, or characteristics of the dwelling units, such as lot size. For water-using appliances, the frequency of use is in large part determined by the number of persons in the dwelling. The biggest use of residential water is for bathroom purposes and this should be a function of the number of persons per dwelling unit (Grima, 1972, p. 86). The number of persons should also determine total annual domestic water use and reflect any economies of scale present in water consumption (Howe and Linaweaver, 1967, p. 20).

In Howe and Linaweaver's (1967) examination of domestic water use in thirty-nine study areas, the variable, number of people per dwelling unit, was used to explain water consumption with mixed results. It was significant in explaining the average yearly demand for domestic water by individual household for dwelling units in apartment areas with flat rates and public sewers, and was the only significant variable in metered areas with septic tanks (Howe and Linaweaver, 1967, p. 24). They derived the following equations for water use in these areas (1967, p. 24):

flat rate and apartment areas with public sewers

$$q_{a,d} = 28.9 + 4.39v + 33.6d_p \qquad R^2 = .90$$

t-statistic 7.87** 3.97**

metered areas with septic tanks

$$q_{a,d} = 30.2 + 39.5d_p \qquad R^2 = .96$$

t-statistic 8.48**

where:

$q_{a,d}$ = annual average water use in gallons per dwelling per day;

v = market value of the dwelling in thousands of dollars;

d_p = persons per dwelling.

Persons per dwelling were found to be insignificant, and had the wrong sign when used to explain domestic water use in metered and public sewered areas (Howe and Linaweaver, 1967, p. 24). The poor showing in these latter areas may have been due to the use of area averages as observations to produce the equation (Morgan, 1973, p. 1065). Averaging the number of persons per household for each set of observations reduces the variance of this statistic in relation to the quantity of water demanded (Morgan, 1973, p. 1065). Morgan suggests that water use projections based on the Howe and Linaweaver model could lead to inaccurate per capita water use estimates if the number of people per dwelling unit is not approximately the same as the sample mean (1973, p. 1067).

Morgan has conducted his own study to determine the influence of persons in each household on the amount of water demanded (1973, p. 1065). He examined ninety-two single family homes in metered and public sewered areas for three different time periods (1973, p. 1066). Also included in his equation was the assessed value of each property in thousands of dollars as a second independent variable (1973, p. 1065). Of the three equations he derived, for the periods November to December, January to February, and both periods combined, he found that the coefficients for both the number of persons per dwelling and the assessed value were significant and had positive signs, but, that the R^2 was relatively low (Morgan, 1973, p. 1066).

The number of persons per dwelling was also significant in explaining residential water use in Fourt's (1958) research. He used this statistic with two other variables, the price of water, and the number of days of rainfall in the summer (1958, p. 7). His analysis was conducted in three parts. First, he examined twenty-three small cities, then, he looked at twenty-one large cities, and finally, he combined both groups together (1958,

p. 7). In the results of his analysis, the number of persons per meter was significant only for the large cities, and the combined sample (1958, p. 8). The final equations for these two samples were (1958, p. 8):

the large cities:

$$x_1 = 5.829 - 0.414x_2 - 0.026x_3 - 0.339x_4 \qquad R^2 = .84$$

t-statistic 5.67** 3.71** 6.28**

the combined sample:

$$x_1 = 5.812 - 0.386x_2 - 0.037x_3 - 0.305x_4 \qquad R^2 = .68$$

t-statistic 5.22** 5.29** 4.77**

where:

x_1 = annual quantity of residential water in thousands of cubic feet used per person;

x_2 = price of 1000 cubic feet of water per month;

x_3 = number of days of rainfall during the months of June, July, and August, 1955;

x_4 = average number of persons per water meter.

Persons per dwelling may not be the only density variable with significant influence on residential water consumption, as the density of dwelling units may also be important. It has been proposed to use the number of lots present to estimate the amount of water used in a given area (Becker, Bizjak, and Schulz, 1972, p. 415). The per capita use of water increases as one moves from rural to suburban areas, and then declines from the suburban areas to the central city areas. The cause of this phenomenon is the presence of large lawns in suburban areas and multi-family dwellings and apartments in central city areas (Flack, 1967, p. 1341).

The size of residential lots appears to be the best measure of dwelling unit density, because it gives an indication of the amount of area devoted to lawns. Linaweaver, Geyer, and Wolff (1964, p. 1121) found that in an average neighborhood of middle income families in Baltimore County, Maryland, each 8,000 square feet of lawn area received an average of 8.5 inches of water in the sprinkling season of 1963. They assumed lot size, as well as weather and the amount of water metering, to be the most important variables influencing sprinkling (1964, p. 1128). Howe and Linaweaver (1967, p. 25) reported the amount of irrigable area between the observations (1967, p. 28). Wolff (1961,

p. 1253) examined water consumption between dwelling units on various sized lots. He found that the average day demand for water increased as the size of the lot increased. His results appear in Table B.

The ratio of peak hour to average day demand also increases with lot size (Wolff, 1961, p. 1253). He found a linear relationship between the size of a residential lot and the total demand during periods of heavy sprinkling, and suggested that when designing new distribution systems in residential areas, it may be more profitable to examine lot size instead of population (1961, p. 1253).

In the equations which Grima (1972, p. 105) derived to explain residential water consumption for single family homes, lot size did not prove to be a significant explanatory variable. Grima (1972, p. 44) suggests that the amount of lawn watering may be related more to income than to lawn size, since, in most cases, lawns are greener where incomes are higher.

Gardner and Schick discovered that lot size was significant in their study of daily per capita water use (1964, p. 12). Their results show that if lot size increases one percent per capita, water use increases 0.15 percent (1964, p. 12). The small increase in water use with increases in lot size could be due to the watering characteristics of cities in the study containing large lots. Often in these communities, alternative irrigation systems were originally employed for lawn and garden watering. Today, in these areas, the residents often let much of their land lay idle (Gardner and Schick, 1964, pp. 15-16).

The number of persons in an area residing in multi-family units is also indicative of the amount of water used for non-domestic uses. Linaweaver, Geyer, and Wolff (1967, p. 269) found that the average annual water use, per dwelling unit, in the five apartment areas which they examined, was 191 gallons per day. This is much less than in residential areas of detached homes, because of the smaller amount of lawn area per dwelling unit associated with apartments (Linaweaver, Geyer, and Wolff, 1967, pp. 269, 271). Peak water use, per dwelling unit in apartment areas, was found to be much less than in areas of detached homes. Peak hourly water consumption in metered public watered and sewered areas was 2480 gallons per day in the West, and 1830 in the East, but only 960 in apartment areas (Linaweaver, Geyer, and Wolff, 1967, p. 269). In contrast to these results, Grima (1972, pp. 103-15) found greater water use per dwelling in townhouses than in single family dwellings.

Water use per acre may be greater in apartment areas than in areas of detached homes. Maximum hour demands have been found to be greater per acre in areas of group houses than in areas of detached homes (Wolff, 1961, p. 1255). The results of Wolff's

(1961, p. 1255) analysis showed maximum hour consumption to be 3.8 gallons per minute per acre for group dwellings, and between 1.8 and 2.9 gallons per minute per acre for detached dwellings. These results suggest that the greater the density of dwelling units in an area, the greater the total residential water consumption. There are two reasons for this: first, dwelling units in apartment buildings are usually not individually metered and the residents may therefore use water more freely, and second, the population density will be greater in apartment areas than in areas of single family homes.

The literature of water consumption cites many other variables that may have some influence on residential water demand. Age of the dwelling may be indicative of the condition of the water pipes and the possibility of water leakage (Howe and Linaweaver, 1967, p. 20). Changing social tastes may have an influence on water consumption by placing more importane on cleanliness and personal hygiene (Sewell and Bower, 1968, p. 25). Changing social tastes may also cause the public to prefer products or services that increase the consumption of water (Sewell and Bower, 1968, pp. 25-26). The growing number of families with two or more automobiles has increased the per capita demand for water (Heggie, 1961, p. 264). Finally, the water pressure in an area will affect the rates of water flow and subsequent consumption (Howe and Linaweaver, 1967, p. 20).

TABLE B

WATER CONSUMPTION BY TYPE OF DWELLING UNIT

Type of Dwelling	Lot size (sq. feet)	Maximum Day (gpcd)	Average Day (gpcd)
Group House	2,000-2,400	93	48
Detached Dwelling	5,000-7,500	64	51
Detached Dwelling	9,000-12,000	163	67
Detached Dwelling	15,000-25,000	278	80
Detached Dwelling	40,000 or more	564	117

Source: Wolff, Jerome B., "Peak Demands in Residential Areas." Journal, American Water Works Association. LIII (October, 1961), 1251-1260.

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APPENDIX C

COMMERCIAL WATER DEMAND: A LITERATURE REVIEW

BACKGROUND

Commercial water use is a second major source of water demand in America. In 1960, the United States Senate (Committee Print, No. 7, p. 9) reported that eighteen percent of the average daily per capita consumption of municipal water was devoted to commercial uses.

The literature of commercial water use is not as extensive as that for residential use, but a few significant pieces of research have explored much of the water use activity of different commercial establishments. The most important was Wolff, Linaweaver, and Geyer's (1966) survey of water use by various commercial and institutional water users in the Baltimore area. They determined the average day, maximum day, and peak hour water demands of these activities and calculated the 95 percent confidence limit of water use for each. They identified a single parameter for each consuming group ". . . which could describe the design requirement for that establishment as a simple unit of water use" (1966, p. 2).

Water Use by Commercial and Institutional Activities

The different commercial activities and institutions that Wolff, Linaweaver, and Geyer (1966) examined included schools, office buildings, stores, restaurants, social organizations, health care facilities and different service oriented businesses. Many of the institutions included in their study have also been examined in other research. In this section, the different estimates for a variety of commercial activities will be compared.

The analysis of commercial and institutional water use presented here relies heavily on the work done by Wolff. Linaweaver, and Geyer (1966), and Searcy and Furman (1961). Wolff, Linaweaver, and Geyer (1966) examined 186 commercial establishments and institutions in the Baltimore area. Their data sources included quarterly billing records, daily and hourly visual readings of water meters, and water consumption recorders installed on water meters (1966, p. 4). Recordings of water use were made between 1963 and 1965. In some cases, an establishment was observed twice to determine seasonal variations in water consumption (Wolff, Linaweaver, and Geyer, 1966, p. 5).

Searcy and Furman (1961) conducted their research on water use by commercial establishments and institutions in Gainesville, Florida. They calculated the monthly, daily and hourly water consumption of the establishments in their sample. The monthly rates of water use were obtained from records covering the period of October 1, 1958 to April 1, 1960. Daily and hourly readings of water meters of the accounts under observation were made in February and March, 1960 (Searcy and Furman, 1961, p. 1113).

While residential water use is measured on a per capita basis or a per dwelling unit basis, commercial and institutional water use is based on many different parameters, depending upon what is the most applicable parameter for each activity. This makes it difficult to compare the water use by different activities, since they may each be based on a different parameter.

Water use by educational institutions varies according to grade level. The parameter used to measure water use by these institutions is gallons per day per student. However, Searcy and Furman did not find this parameter to be completely adequate because:

> ". . . there is not always a direct relationship between water consumption rates and the number of students in attendance. Variations in water consumption appeared to be more nearly related to special activities of the school. These include lawn watering, sports events, construction work, and other water consuming activities" (1961, p. 1115).

Searcy and Furman (1961, p. 1114) examined nine elementary schools, two junior high schools, two senior high schools and one school containing kindergarten through twelfth grade. The monthly average rates of water use by type of school were 5.8 gpd/student for elementary schools, 6.0 gpd/student for junior high schools, and 15.8 gpd/student for senior high schools. The maximum monthly rates were 12.9 gpd/student for elementary schools, 16.2 gpd/student for junior high schools, and 36.8 gpd/student for senior high schools. Maximum day recorded demands were 10.6 gpd/student for elementary schools, 12.2 gpd/student for junior high schools and 61.3 gpd/student for senior high schools (Searcy and Furman, 1961, p. 1111).

Wolff, Linaweaver, and Geyer (1966) compared water use by both public and private primary and secondary schools. They found the mean annual water use for public schools to be 5.38

gpd/student for elementary schools, 5.64 gpd/student for junior high schools, and 6.63 gpd/student for senior high schools. The mean annual water use for private schools was 2.27 gpd/student for elementary schools, 10.4 gpd/student for senior high schools, and 8.49 gpd/student for combined schools containing grades one through twelve. The maximum day recorded rates of consumption in public schools were 6.84 gpd/student for elementary schools, and 15.2 gpd/student for senior high schools. The maximum day recorded consumption for private schools was 3.10 gpd/student for elementary schools, 15.7 gpd/student for senior high schools, and 16.8 gpd/student for combined schools (Wolff, Linaweaver, and Geyer, 1966, p. 9).

Water use in schools occurs primarily in one limited period of the day, and the peak water use at certain specific times. Ninety-three percent of the water consumed in elementary and junior high schools is during a ten hour period (Searcy and Furman, 1961, p. 1116). Most water use in schools appears to occur between 6:00 a.m. and 6:00 p.m. on weekdays. (Wolff, Linaweaver, and Geyer, 1966, p. 13; Searcy and Furman, 1961, pp. 1114-15). Peak water use in elementary schools and junior high schools occurs around noon. High schools experience two peaks, one around noon, and another in the late afternoon. (Wolff, Linaweaver, and Geyer, 1966, pp. 12-13; Searcy and Furman, 1961, pp. 1114-15). "The effect of showers following the sports program explains the second peak in the consumption rates of the high schools. . ." (Searcy and Furman, 1961, p. 1116).

Other variables beside grade level and whether they are public or private affect water consumption in schools. The age of a school is such a variable. Searcy and Furman (1961, p. 1112) found that, in general, the older the school, the smaller the water consumption per student. It has also been reported that the presence of showers and cafeterias in schools have significant influence on water consumption (Public Works, 1957, p. 108).

Water consumption in colleges is dependent upon whether students live on campus or not. The range in water consumption for colleges with resident students was 63.3 gpd/student to 169 gpd/student, but only 2.05 gpd/student to 15.2 gpd/student for colleges without resident students (Wolff, Linaweaver, and Geyer, 1966, p. 15). The mean school year water consumption for colleges was 106 gpd/student for institutions with resident students and only 5.4 gpd/student for colleges without students in residence. (Wolff, Linaweaver, and Geyer, 1966, p. 16). The above results for schools without resident students should be approached with caution as they were derived from a sample containing only two schools, one of which had limited water using facilities (Wolff, Linaweaver, and Geyer, 1966, p. 15).

The parameter selected by Wolff, Linaweaver, and Geyer (1966, p. 18) to explain water use in hospitals was the number of beds present. The data showed that as the cost of patient care increased, so did water use. The cost of patient care was not used to predict water use because it was difficult to obtain cost data (Wolff, Linaweaver, and Geyer, 1966, p. 17). They examined nine hospitals and found the average annual water consumption to be 346 gallons per day/bed (1966, p. 18). Maximum day recorded consumption was 551 gpd/bed (Wolff, Linaweaver and Geyer, 1966, p. 19). Searcy and Furman (1961, p. 1117) discovered average water use in hospitals to be only 275 gpd/bed. Peak water demands in hospitals occur in the late morning, the early afternoon, and the late afternoon or early evening. (Wolff, Linaweaver, and Geyer, 1966, p. 21).

Water consumption in nursing homes and special institutions like orphanages or mental institutions were also measured in gallons per day per bed. The average annual use in the institutions observed was 133 gallons per day per bed with a range of 92.2 gpd/bed to 210 gpd/bed (Wolff, Linaweaver, and Geyer, 1966, p. 22). The period of peak water use in these institutions occurs between two and five in the afternoon (Wolff, Linaweaver, and Geyer, 1966, p. 23).

Two types of apartments, four high-rise apartment buildings, and five garden-type apartment buildings, were included in the commercial water use research project (Wolff, Linaweaver, and Geyer, 1966). The parameter selected to explain water use in apartments was water use per occupied unit. The average annual use was 218 gpd/unit occupied for high rise apartments and 213 gpd/unit occupied for garden apartments (Wolff, Linaweaver, and Geyer, 1966, p. 25). The maximum day recorded demand was 426 gpd/unit occupied in high rise apartments and only 215 gpd/unit occupied for garden apartments (Wolff, Linaweaver, and Geyer, 1966, p. 25). Peak water use in high rise apartments occurs from ten in the morning to three in the afternoon and from six to seven in the evening. In contrast, peak water use in garden apartments occurs between seven and nine in the morning and six to seven in the evening. The evening peak water demand in garden apartments increases as lawn sprinkling increases in the summer (Wolff, Linaweaver, and Geyer, 1966, p. 26).

Water use in two downtown Baltimore hotels was measured in gallons per day per square foot. The mean annual water use in the two hotels was 0.256 gpd/square foot, and the maximum day recorded demand was 0.294 gpd/square foot (Wolff, Linaweaver, and Geyer, 1966, p. 28). According to Wolff, Linaweaver, and Geyer (1966, p. 30), water use in motels is very much like that in hotels. They used the same parameter for motels as they did for hotels and found mean annual water use was 0.224 gpd/square foot and the peak recorded demand was 0.278 gpd/square foot (1966, p. 31). Though they found water use per square foot to be greater in hotels than motels, this situation is due to the presence of more public rooms in hotels than motels. Water use per living unit is much higher in hotels than motels (1966, p. 30).

Data on motel water use has also been collected on a per guest basis. (Searcy and Furman, 1961, p. 1117). The average monthly water consumption in the six motels Searcy and Furman examined was 63 gpd/guest, and the maximum monthly consumption was 181 gpd/guest (1961, p. 1112). In 1961, the average water use in motels per dwelling unit in ten cities and counties varies from 50 gpd/housing unit to 196 gpd/housing unit ("Water Demands of Decentralized Community Facilities", 1961, p. 104).

When measuring water use in office buildings, Wolff, Linaweaver and Geyer (1966) differentiated between general purpose office buildings and medical offices. The parameter used to measure water use in both was consumption per square foot. The general purpose office buildings were divided into two groups, those ten years or older, and those younger than ten years. Average annual water use was 0.093 gpd/square foot for office building less than ten years old, 0.142 gpd/square foot for office buildings over ten years old, and 0.618 gpd/square foot for medical office buildings (Wolff, Linaweaver, and Geyer, 1966, p. 34). Only two observations were made of medical office buildings, but both had substantially higher water use than general office buildings. The greater water consumption in older office buildings as compared to younger buildings could be due to leakage in the older water systems, discharge of water in their cooling units, and more inefficient utilization of water (Wolff, Linaweaver, and Geyer, 1966, p. 33).

Sales area was used as a design variable for department stores. Mean annual water use in five department stores in the Baltimore area was 0.216 gpd/square foot of sales area and the maximum day recorded use was 0.388 gpd/square foot (Wolff, Linaweaver, and Geyer, 1966, p. 38). Water use in department stores is subject to the types of amenities they offer, such as restaurants, and restrooms (Wolff, Linaweaver, and Geyer, 1966, p. 38).

Gross floor area was selected to describe water use in two shopping centers in Towson, Maryland. The average annual water use for both was 0.169 gpd/square foot, and the maximum day recorded demand was 0.232 gpd/square foot (Wolff, Linaweaver, and Geyer, 1966, p. 41). Searcy and Furman (1961) also used gross floor area to describe water use in a shopping center. They found the average monthly consumption was 0.209 gpd/square foot, and the maximum monthly use was 0.278 gpd/square foot (1961, p. 1113). Water use per square foot in shopping centers may be influenced by the presence of restaurants, cafeterias, and self-service laundries ("Water Demands of Decentralized Community Facilities", 1961, p. 103).

Water use in a single car wash was measured by the floor area of the building. Mean annual water use was 4.78 gpd/square foot and the maximum day recorded use was 8.72 gpd/square foot (Wolff, Linaweaver, and Geyer, 1966, p. 43). They discovered the maximum demands for water at the car wash included in their study was in the winter (1966, p. 45).

The floor area of the garage and office was the parameter used by Wolff, Linaweaver and Geyer (1966) to measure water use in six service stations. The mean annual water use for the six was 0.251 gpd/square foot and the range in water use for the stations was 0.159 gpd to 0.443 gpd/square foot (Wolff, Linaweaver, and Geyer, 1966, p. 45). The ratio of peak hour water demand to mean for days recorded was 19.5--this probably denotes the effect of car washing (Wolff, Linaweaver, and Geyer, 1966, p. 45).

Other measures have been made of service station requirements. In a survey of sanitary engineers ("Water Use and Sewage Volume Away from Home", 1957, p. 108), to determine the design requirements of different commercial and institutional activities, suggestions were made as to how much water should be allowed for use by service stations. One recommendation was to allow five gallons of water per day for each car. Another also suggested five gallons per car, but also thirty gallons per day for each employee ("Water Use and Sewage Volume Away from Home." 1957, p. 108).

Two types of laundries were included in the Commercial Water Use Research Project. Wolff, Linaweaver, and Geyer, (1966) combined commercial laundries and dry cleaners, and laundromats. The design parameter for both was floor area. The average annual water use was 0.253 gpd/square foot for commercial and dry cleaning establishments, and 2.17 gpd/square foot for laundromats. Peak water use was available for only laundries and dry cleaners; the ratio of maximum day recorded water use to the mean for days recorded was 1.29 (Wolff, Linaweaver, and Geyer, 1966, p. 48).

A great many estimates have been made for water use in restaurants. A survey made in 1961 ("Water Demands of Decentralized Community Facilities", p. 105) stated water use per seat in restaurants across America vary from 20 gpd to 120 gpd. The same survey also reported water use on the basis of meals served, where water use varied from 2.6 gallons to 15 gallons per meal (1961, p. 105). An earlier survey of water use made in 1957 ("Water Use and Sewage Volume Away from Home", 1957, p. 109) reported much the same type of water use in restaurants, but it also allowed for an additional two gallons per person served in bars and cocktail lounges. Searcy and Furman (1961, p. 1113) measured water consumption in two restaurants and one cafeteria based on per meal use. They found the average monthly consumption was 7.7 gpd/meal and the maximum monthly consumption was 17.3 gpd/meal. (1961, p. 1113).

Wolff, Linaweaver, and Geyer (1966) divided the restaurants in their sample into three groups, drive-in restaurants with seating facilities, drive-in restaurants with little or no seating, and traditional restaurants. The parameters they used for design purposes were water use by car space for drive-in restaurants with little or no seating, and water use by seat for drive-ins with seating and traditional restaurants. The mean annual use for these three types of restaurants was 109 gpd/car space for drive-ins without seating, 40.6 gpd/seat for drive-ins with seating, and 24.2 gpd/seat for traditional restaurants (Wolff, Linaweaver, and Geyer, 1966, p. 51).

Social clubs examined included golf clubs, swimming clubs, and boating clubs. The parameter used to describe water use in each was the number of the family or individual memberships. The mean annual demand for water by golf clubs was 66.1 gpd/membership, for swim clubs, it was 16.5 gpd/family memberships, and 10.5 gpd/membership for boating clubs. (Wolff, Linaweaver, and Geyer, 1966, p. 54).

The number of members was selected as the design parameter to describe water use for churches. Mean annual use in two churches was 0.138 gpd/member, and maximum day recorded use was 0.862 gpd/member. (Wolff, Linaweaver, and Geyer, 1966, p. 55).

Water consumption by barbershops was measured in use per chair. In six barbershops, the average annual use was 54.6 gpd/chair. (Wolff, Linaweaver, and Geyer, 1966, p. 56).

An activity similar to barberships are beauty salons where the number of stations was used as the predictor variable for water use. The mean yearly water use for eight salons was 0.269 gpd/station (Wolff, Linaweaver, and Geyer, 1966, p. 58).

Supermarkets vary considerably in the amount of water they consume in their operation. In a survey of sixty supermarkets, ranging in size from 4,600 to 35,000 square feet, water consumption per 1,000 square feet ranged from 24 to 3,370 gpd ("Water Demands of Decentralized Community Facilities," 1961, p. 104). This wide variation in water demand must depend upon many different effects including: "Degree of business activity, number of employees, clean-up practices, butchering conditions, form of air-conditioning and washing and repackaging of vegetables." (Water Demands of Decentralized Community Facilities," 1961, p. 104).

Water use on highways refers to the restrooms and restaurants serving these transportation routes. Total water use per service area has been estimated at 25,000 gpd on the Sunshine Parkway in Florida, and 10,000 gallons per day at rest areas in Georgia ("Water Demands of Decentralized Community Facilities", 1961, p. 103). The average number of persons per vehicle stopping at rest areas has been estimated to be between 1.5 and 3.5. The percentage of those stopping at rest areas and using the restaurants has been estimated at both 15 percent and 80 percent. Between 90 and 100 percent of those people stopping at rest areas use the rest rooms. ("Water Demands of Decentralized Community Facilities", 1961, p. 103).

Many other commercial activities have been examined to determine their water use. These activities and estimates have included the following: Drive-in theaters, 3 and 7½ gpd/car; airports 3 to 5 gallons per passenger; trailer camps, 100 to 150 gpd/trailer space; and theaters, 1 to 5 gallons per seat ("Water Use and Sewage Volume Away from Home," 1957, pp. 108-9, 210).

Forecasting Models

Few forecasting models of commercial water use have been developed, but the ones presented here are either based upon extending past trends into the future or using Wolff, Linaweaver and Geyer's (1966) data as a basis for forecasting water use by individual commercial activities. Strand (1966) provides a four step method of forecasting future daily commercial water use based on past consumption trends. The four steps are: First, plot past annual water sales and extend the line that best fits the data to the desired year and find the future daily demand; second, plot the past number of meters present and the use in gallons per day separately, extend these trends into the future, and combine the results to get future water use; third, plot annual water sales per capita per day, then estimate the future daily water demand by using an estimate of future population; and fourth, after examining the above estimates, select a figure of water use that is a compromise between the various estimates (1966, p. 523).

A second approach examines each commercial and institutional activity separately, using data obtained by Wolff, Linaweaver, and Geyer (1966). Hittman associates (1969) in their Main II. system devised water forecasting equations for twenty-eight categories of institutional and commercial water users (p. V-1). These forecasting equations used data obtained by Wolff, Linaweaver, and Geyer in the 1960's. The water demand for each of commercial and institutional activities, Hittman associates examined, were estimated using the following equations (p. V-3):

Mean annual requirements:

$$\overline{q}_c = \overline{C}Pc$$

Maximum day requirements:

$$(qc)_{mxdy} = C_{mxdy}Pd$$

Peak hour requirements:

$$(qc)_{pkhr} = C_{pkhr}Pc$$

where: $\overline{q}c$ = mean annual water requirement for category c.

$(qc)_{mxdy}$ = maximum day water requirement for category c.

$(qc)_{pkhr}$ = peak hour water requirement for category c.

$\overline{C}$ = mean annual coefficient for category c.

C_{mxdy} = maximum day coefficient for category c.

C_{pkhr} = peak hour coefficient for category c.

Pc = value of water use parameter for category c.

Growth models of commercial water uses were based on projections of past consumption as measured by the parameters. The values of these parameters are projected to the desired future year and water use is estimated in that year. (Hittman associates, 1969, p. V-5). Unfortunately, they found it very difficult, in most cases, to get data on the values of these parameters for past years. They selected an alternative method for projecting the parameter values by using employment data. They explained this choice as follows (p. V-6):

> "The basic assumption implicit in this method can be stated: For a specific category, in a specific place, the relationship between employment and the water use parameter is presumed constant over time. If the water use parameter is a valid measure of the activity within the category, this amounts to a constant productivity assumption, with the important qualification that it applies individually to each category and each place."

The following procedure was employed to estimate the future values of the parameters for each commercial activity when the data on the past value did not exist (Hittman Associates, 1969, p. V-6):

First, a statistical model is developed for employment in each activity--

$EMP'_i = f(EMP_i, X1, X2, \text{etc.})$

where

EMP_i = number of employees in category i;

X1, X2 = other right-hand variables in the growth equation.
ETC.

(') = the project value

Second, the parameter value is projected--

$PAR'_i = (EMP'_i/EMP_i)\ PAR_i$ where: PAR_i = parameter value for cateogory i.

This method of predicting the parameter value was not employed for elementary and secondary schools because the actual parameter values were available (Hittman Associates, 1969, p. V-6).

They found the employment information for some of the categories were grouped together with other commercial categories. This caused them to group these activities together and derive growth equations for the entire group.

These derived growth equations are used to project the future values of the individual parameters in the following manner (Hittman Associates, 1969, p. V-14):

$\Delta EMPi/t = f\ (X1, X2, X3, \text{etc.})$

$EMPi' = \Delta EMPi/\Delta t\ \Delta t + EMPi$

$PAR'_j = PAR_j\ EMP'_i/EMP_i$ WHERE:

EMPi = number of employees in category group i

t = calendar year

X1, X2 = right - hand variables
X3, etc. in growth equation

PAR_j = parameter value for category j

(') = projected value.

The growth equations of the ten groups are similar in the types of variables they contain. Except for the equations for schools, they all contain some measure of population change, whether it is historical or projected change, though none of the equations contain both terms. "The historical term suggests that growth in correlated categories follows increases in population by some log time, but the growth in laundries and total services employment apparently tends to be coincident with population growth". (Hittman Associates, 1969, p. V-14).

A second set of important variables in these equations are the historical and the projected rates of change in total service employment. Those equations that contain negatively correlated historical rates of change in total service employment, also contain the projected total service employment variable which is more heavily weighted." This **may** demonstrate the tendency of individual entrepreneurs to balance expected future business growth against recent increases in capacity". (Hittman Associates, 1969, p. V-15).

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APPENDIX D

INDUSTRIAL WATER DEMAND: A LITERATURE REVIEW

INTRODUCTION

Industrial water consumption is a third major source of water demand on municipal water utilities and is second in importance to that of residential users. In contrast to residential and commercial users, most industries fill demands for water from their own sources. Water use between individual residential and commercial consumers does not vary as much as between different industrial users. This extreme variation is caused by the wide range of activities and manufacturing processes engaged in by industry. Explaining present water use and forecasting future consumption by industry is made difficult by this great variety in industrial processes. Usually, projections of industrial water use are made according to the type of industry involved and by using employment figures.

Water Use in Industry

The percentage of total water demand in America devoted to industrial purposes is substantial. Analyses of municipal water utilities have found that about one fourth of their water is used by industry (Porges, 1957, p. 1577; and U.S. Senate, 1960, Committee Print, No. 7). Municipal water utilities are not the only source of industrial water--many industries have developed their own source of supply. It was estimated in 1965 that industry supplied 1.70 billions of gallons per day of their water needs themselves (Murry, 1965, p. 4). The percentage of fresh water consumed by industry obtained from municipal sources was only about ten percent in the 1960's (Kollar and Brewer, 1968, p. 1130).

The sources of industrial water are varied and changing over time. Kollar and Brewer (1968, pp. 1129-30) summarized these various sources of water in their study of the industrial that account for 97 percent of all industrial water consumed.

> "In 1964, fresh water withdrawals accounted for 11,200 bil-gal. of the total 14,000 bil gal. withdrawal. Company controlled sources provided 9,800 bil gal. of which 8,500 bil gal. were obtained from surface supplies, and

> 1,360 bil gal. from wells. The remaining 1,380 bil gal. were purchased from public water systems." (Kollar and Brewer, 1968, p. 1130).

The remainder of water withdrawn for industrial purposes in 1964 was brackish containing 1,000 ppm dissolved solids (Kollar and Brewer, 1968, p. 1130). Though industries were using more water in 1964 than in previous years, the percentage of total industrial water provided by municipal utilities declined. (Kollar and Brewer, 1968, p. 1133). The relatively minor dependency of industry on municipal utilities is because water from company owned sources and brackish water is lower in cost than municipal water (Kollar and Brewer, 1968, p. 1131).

Industry may obtain relatively little of its water from municipal sources at present, but this may change in the coming years. There are two reasons why this change may occur. First, with water becoming more scarce, new and expensive facilities will be needed to capture and transport it to consumers. Public water authorities may be the only ones able to afford the development of such facilities. Second, as the regulations controlling effluent become more stringent, it may induce industries to connect themselves to municipal water treatment and sewer systems (Howe, 1968, pp. 54-55).

The uses for water in industry are varied, but they can be summarized into four classifications (Kollar and Brewer, 1968, pp. 1132-33). The first classification is process water, which is water used directly with the materials used in the production process. The second classification contains water used for cooling and condensing in stream electric generating plants. The third classification is water employed to cool machinery used in the production process, or the materials undergoing processing. The fourth classification is water used for sanitary purposes and boiler feedwater. Another category can also be included containing water used for sprinkling systems and fire protection. The percentage of water in a factory devoted to each of these categories varies according to the size of the plants. Larger plants devote a greater percentage of the water they use to cooling than smaller plants, but water used for sanitary and service purposes is more important in small plants than large ones (Green, 1951, p. 595).

In 1964, major industrial users of water consumed 3,700 billion gallons in process operations or over 26% of the total water they demanded (Kollar and Brewer, 1968, pp. 1129, 1134). Water for all cooling and condensing purposes accounted for 9,400 billion gallons in 1964 or about two-thirds of all the water used by manufacturers. In some industries, over 85% of all water demanded is devoted to cooling and condensing purposes (Kollar and Brewer, 1968, p. 1133). Murry (1965) reported water used in cooling was even more important than this. According to him, 97% of all water used in thermoelectric plants is for cooling purposes, and for all industrial water combined, 90% is for cooling purposes (1965, p. 4). Sanitary demands for water are small compared to water use in other industrial processes. It has been found to range from twenty to thirty gallons per day per employee (Dickerson, 1970, p. 612). The heaviest demand for sanitary water is usually during the day shift when the office staff is present and the laboratory and maintenance crews are at their maximum size (Dickerson, 1970, p. 612). The amount of water set aside for fire protection varies according to the type of industrial process and hazard involved. Since fire demands often are greater for industrial plants than commercial or residential structures, the water pressures are nearly twice as great. Usually a factory must maintain its own water storage and fire water distribution system. (Dickerson, 1970, p. 612).

Most industrial water is consumed by only a relatively few industrial plants and by a few major industry groups. Less than three percent of all the major industrial water users in the United States consume more than ninety-seven percent of all the water used in industry (Kollar and Brewer, 1968, p. 1130). Five industries, metals, chemicals, pulp and paper, petroleum and coal, and food processing use about eighty-five percent of the water used in industry (Ruble, 1965, p. 831). Data reported by Feth in 1973 showed an even greater concentration of water use in these five industry groups (p. I 12). He reported primary metal industries annually withdrew 3,899 billion gallons; paper and allied products withdrew 2,078 billion gallons; petroleum and coal products withdrew 812 billion gallons (1973, p. 112). Water use for an industry group can vary substantially from one factory to another. Pulp and paper mills use between twenty and sixty million gallons a day. (Guthrie, 1969, p. 533). Chemical plants consume between a few hundred thousand gallons a day to several million a day (Dickerson, 1970, p. 612).

McGregor (1968) analyzed water use in different industries in Northern Georgia to discover how it was employed in various production processes. Forty-four four-digit standard industrial code industries were selected for analysis (McGregor, 1968, p. 66). Water users were broken down into five categories based on the amount of water withdrawn annually per employee. (Table C-1).

TABLE C.

INDUSTRIAL WATER USER CATEGORIES

CATEGORY	PER EMPLOYEE REQUIREMENT (THOUSANDS GALLONS)	NUMBER OF FOUR-DIGIT INDUSTRIES
I.	1-9	23
II.	10-99	10
III.	100-199	5
IV.	200-299	3
V.	300 or more	3

Source: McGregor, John R. "An Approach to the Regulation of Water Use in Manufacturing: A Study of North Industries." Proceedings of the Indiana Academy of the Social Sciences. (1968), p. 70.

Water used in Category I. industries was nearly entirely used for drinking, washroom, and sanitation purposes. The major use of water in Category II. industries was for drinking, washroom, and sanitation purposes, as a material in the production process, and for washing and cooling machinery. Water use in groups III., IV., and V. was similar to that in categories I. and II. except for significant use of water in rinsing, scalding, cooking, and sterilizing in food processing (McGregor, 1968, pp. 69-72).

Water use in separate elements of the production process may be subject to changes in social taste. If consumer preferences change from one product to another, this can cause increases in water used in production (Sewell and Bower, 1968, pp. 25-26).

Seasonal variations can also cause fluctuations in the amount and types of water use. Climatic changes through the year can affect how much water is used for cooling (Sewell and Bower, 1968, p. 35). The rate of production may vary according to the time of the year, as in the automobile industry, where more cars are produced in the first half of the year (Sewell and Bower, 1968, p. 36). The type of product produced may vary by the season of the year. The demand for gasoline is greatest in the summer, whereas for heating fuel, the peak demand occurs in the winter. (Sewell and Bower, 1968, p. 36). Daily water use can be affected by fluctuations in the rate of the incoming raw materials, or by equipment failures. (Sewell and Bower, 1968, p. 39).

Each production process involved in industry may require a specific grade of water. Industry may demand one quality of water for boiler water, another for cooling water, and one each for the different processes involved in the production line (Guthrie, 1969, p. 533). Industrial production is generally of two types--either simple, where there are just a few different processes involved, or complex, where there are many different processes present--each requiring a different quality and quantity of water (Brewer, 1968, pp. 90, 93). Vaughn (1971, pp. 144-46) has summarized the types of water involved in industrial production into three categories. First, is high quality water that is relatively unaffected by the production process. An example of this is cooling water which many times is maintained in closed systems and does not experience any significant change in quality. Second, is low quality water whose quality is significantly altered by the production process. Third, is a high quality water that is also significantly affected by the production process. The most important requirement of industrial water is the uniformity in its quality level. "It is usually possible to compensate for deficiencies in the desired standard, but it is nearly impossible to adjust for unexpected variations." (Guthrie, 1969, p. 533).

Since completely pure water is not needed in some industrial processes, industry engages in the recycling of water. Kemmer (1970, p. 708) describes three approaches taken by industry in recycling water. First, some industries employ the effluent from municipal sewage plants for use in their production processes. A second older method is for a plant located downstream from other plants and cities to collect their discharges. Though this is easily accomplished, it means the industry collecting the effluent may be exposed to contamination of various strengths and types. Finally, many plants recycle their own water, employing the highest quality water in the most sensitive processes, and recycling the poor quality water into less sensitive areas.

The recirculation of water within a plant is very common and has been increasing over time. The rate of recirculation is defined as the ratio of the gross water used in a plant over the water pumped into the factory (Kollar and Brewer, 1968, p. 1133). The recirculation rate in 1964 for large water using industries was 2.18; in 1954, it was 1.86 (Kollar and Brewer, 1968, p. 1133) The recirculation ratios of the five largest water consuming industries, chemicals, petroleum, pulp and paper, food processing, and primary metals, increased at an annual rate of 1.8 percent between 1954 and 1964. (Stewart and Metzger, 1971, p. 156). The recirculation of water by industry has been found to be greater in areas where water is scarce (Kollar and Brewer, 1968, p. 1135).

An industry's decision to recirculate water depends on the grade of water to be recycled, and the costs incurred. It is usually profitable to recycle low grade water whose quality is significantly affected by an industrial process, where high quality is not demanded (Vaughn 1971, p. 146). High quality water, which may be used in closed cooling systems not affected by the industrial process, demands little more than to be cooled to a lower temperature for reuse. (Vaughn, 1971, pp. 144-45). In contrast, it may be very expensive to recycle a high grade water whose quality is severely affected by an industrial process, since the necessary facility may be more advanced than normal sewage treatment plants (Vaughn, 1971, p. 146). Water whose quality has been significantly affected can be recirculated back into a factory, but it may be employed in a process not demanding a high standard of quality.

The extent of water recirculation depends on what process it has been employed in. Except for refineries, where cooling water may be recirculated over twenty times, few factories recirculate substantial amounts of cooling water, and most is discharged. (Kollar and Brewer, 1968, p. 1133). About one third of the factories surveyed in 1964 recirculated boiler feedwater and sanitary water, but since this is a small portion of the water used in manufacturing, the amounts recirculated are not very significant. (Kollar and Brewer, 1968, p. 1134). Large amounts of water used in process operations are recirculated in part to recover materials and products. The recirculation rate of process water may be about 4.5 (Kollar and Brewer, 1968, p. 1135).

Recirculation is a function of technology which is an influential variable on many aspects of industrial water use. Technological change can manifest itself in many ways, such as new products, new industrial processes, new kinds of raw materials, and new methods in handling water. (Sewell and Bower, 1968, p. 24). The influence of technology is difficult to measure for two reasons. (Sewell and Bower, 1968, pp. 24-25). First, forecasts of technological change are difficult to make, especially beyond five or ten years. Second, the adoption rate of new technology is unknown. "We have a basis in past history for estimating the rate of innovation, but recognized urgency, higher costs of water, or other causes contributing to concerned efforts may introduce a new trend." (U.S. Senate, Committee Print, No. 32, 1960, p. 32).

Water use and water recirculation are also dependent upon the presence of effluent charges levied on industry.

> "Increased use of sewer rental charges, based on the amount of water used as a method of financing sewerage and sewage treatment, has a tendency to increase water conservation and reduce the use of water. On the other hand, when sewer service charges are based on the strength of the sewage, there is a tendency to use more water for transportation of the wastes than is really needed, in order to reduce the strength of the sewage." (U.S. Senate, Committee Print, No. 7, 1960, p. 16).

Elliot (1973) conducted a statistical analysis to determine the influence of surcharges on industrial wastes. He found a ten percent increase in sewage surcharges caused a decrease of around eight percent in the amount of wastes discharged by industry. A similar increase in sewage surcharges caused a decrease of six percent in the water used in industry. (1973, pp. 1127, 1129).

The effect of price on water demand is large enough to influence industry's consumption. Afifi (1969, p. 41) reported that the demand by large industrial consumers for water is more elastic than for residential consumers. Industries that produce more expensive products per 1000 gallons of water will find their production process less affected by increases in the price of water than industries producing goods lower in price in relation to the cost of water. (Kollar and Brewer, 1968, p. 1137). Usually, the cost of water is a small portion of the per unit cost of a product, ranging from about 0.1 to 5.0 percent. (Sewell and Bower, 1968, p. 22).

Statistical analyses have shown the price of water to be significant in determining the demand for industrial water. Elliot (1973) found the price of water to be significant in explaining both the amount of industrial wastes discharged and the amount of water consumed. His derived equations are as follows (1973, pp. 1128-29):

For waste treatment:

$$T = 13.11 - 1.46S - 120.00\,G + 36.20\,P$$

For water:

$$W = 2.22 - 36.79\,N - 0.52\,S + 8.63\,P + 75.10\,FK$$

Where:

T = pounds of B.O.D. per $1,000 value added in manufacturing

S = surcharge in dollars per 1,000 lb. of B.O.D.

G = gross marginal cost of water and normal sewer in dollars per 1,000 gallons

P = price of labor in dollars per hour

W = gallons of water per day per $1,000 value added to manufacturing

N = net marginal cost of water and normal sewer in dollars per 1,000 gals.

FK = proportion of city value added, accounted for by food and kindred products

The difference between variables G and N in the above equations has to do with the amount of sewage discharge, industries are permitted. The sewer charge included in variable G is a fixed percentage of the water charge. However, for variable N, the sewage surcharge does not account for all the sewage discharged, but only that above a certain minimum level of concentration (Elliot, 1973, p. 1123). The coefficient of determination for the two equations by Elliot are quite low, only 0.17 for his waste treatment equation, and 0.32 for his water equation (1973, pp. 1128-29).

Another analysis of the effect of price upon industrial demand for water was conducted by De Roog (1974). He divided industrial water into four types; cooling, processing, steam generation and sanitation and measured the impact of price on the first three. His price variable (P_{Gjt}) is a weighted mean and takes into account the price of both new water and recycled water. This price variable is defined in the following equation (De Roog, 1974, p. 404):

$$P_{Gjt} = [P_{wjt} + g_{wjt} + P_{rjt} (G_{jt} - g_{wjt})]/G_{jt}$$

where:

P_{wjt} = price of new water

P_{rjt} = price of recycled water

G_{jt} = gross water use

g_{wjt} = quantity of intake water

The cost of new water and recycled water includes many different costs such as maintenance costs, the cost of water brought from a public water utility, and capital costs (DeRoog, 1974, p. 404). The equations he derived included three variables, the price variable, a value of output variable, and a technology index which measures capital and labor inputs. (1974, pp. 404-5). His results showed that as the cost of water increases, its use in cooling, processing, and steam generation declines (1974, pp. 405-6).

Increases in the price of water may in some instances not cause declines in water consumption, if other costs to industry are increasing at a faster rate. Seagraves (1972, p. 476) suggests this may occur where the cost of labor is increasing faster than the cost of water, so that water is substituted for labor in dealing with industrial wastes.

Forecasting Industrial Demand for Water

To project future industrial use of water requires an understanding of many different variables. Some simple forecasting equations have been developed to project industrial water consumption, but they overlook many of these influential variables that are discussed in only a few forecasting models.

Projections of water demand by manufacturers are often just extensions of present water use trends. Strand (1966) offers one such forecasting model. His procedure for estimating future average daily industrial water demand involves three steps as follows: "(1) plotting annual sales (not including large users) and reducing to future daily demand, (2) discussing with large industrial users their needs for water in the future, including determination of present hourly use on maximum day by field study, and (3) adding the two estimates to determine future demand" (Strand, 1966, p. 523).

Forecasting methods have become more sophisticated in recent years with the addition of the study of employment in industry and examining industry groups separately. The amount of water withdrawn by a plant appears to be a function of the number of employees working in the factory (Green, 1951, p. 594). Stewart and Metzger (1971) produced a ratio forecasting future industrial water based not only on changes in employment, but also changes in recirculation and output. Their ratio is the following (1971, p. 155):

$$F = EO/RT$$

where:

F = ratio of future to present industrial water use.

E = ratio of future employment in industry to present employment.

O = ratio of future industrial output per employee to the present value

R = ratio of future use of recirculated water to present recirculation

T = ratio of present gross water use per unit of production to the gross water requirements in the future.

Stewart and Metzger (1971) have estimated what the values of the variables in their equation will be. They report industrial employment is increasing at a rate of about one percent annually (1971, p. 156). The measure of industrial productivity, variable O, is increasing at an annual rate of almost three percent, and for the large water using industries, the rate is between two and four percent annually. (Stewart and Metzger, 1971, p. 156). The recirculation ratios of the five largest water using industries increased 1.8 percent between 1954 and 1964. They estimate that for industry in general, recirculation will increase at a rate of two percent annually (1971, p. 156). Finally, they forecast the value of T will be about 1.5 in fifty years and will almost eliminate the influence of increases in industrial employment. (1971, p. 157).

Mercer and Morgan (1974) used an approach also considering employment, but broke industry down into categories defined by two digit standard industrial codes. They derived two equations, one for estimating water use per employee for each industry category, and one for estimating employees in firms not covered by the census of water use. These equations were (Mercer and Morgan, 1974, p. 797):

Water use per employee:

$$W_i = OT_i/N_i$$

where:

W_i = water use per employee in the ith two digit standard industrial code.

OT_i = sum of water use by firms in the ith two digit standard industrial code.

N_i = sum of employment in ith two digit standard industrial code.

Employment by firms:

$S_i = L_i/R_i$

where:

S_i = the average employment of a firm in the ith industry

L_i = total employment in the ith industry minus the employment of the firms included in the census of water use;

R_i = number of firms in the ith industry minus those included in the census of water use.

The second equation was employed only to gain information on industries too small to be contained in the census of manufacturing. If their model is used to calculate water use for a number of years, trends may be observed and can be useful in planning future water facilities (Mercer and Morgan, 1974, p. 800).

A related technique was employed by Rollins, Allee, and Lawson (1969) to project industrial water use per employee in hydrological areas in the North Atlantic Region. They used three forecasting procedures. In the first, they multiplied water intake and discharge by employee by estimates of employment change. The second was output based where the water intake and discharge per employee was multiplied by estimates of employment and output by employee. The third equation was similar to the second, but included projected changes in the amount of water recycling. (Rollins, Allee, and Lawson, 1969, pp. 36, 40). Projections of employment based on past experience may be dangerous, especially if based on a short time period, because the employment rate may have made dramatic changes with fluctuations in the economy. (Staley, 1960, p. 12).

Staley (1960) derived a model for estimating what portion of total water consumed in a city would be devoted to industrial activities. The purpose of his model was to determine how much industrial employment a river basin can support. Not all water in a river basin can be devoted to industrial consumers, since residential and commercial users must also be supplied. He derived three simultaneous equations to obtain, estimates of the amount of industrial employment, the amount of water used by industry, and the amount of water used in homes and commercial establishments. (Staley, 1960, p. 7). His first equation determines industrial water consumption (1960, p. 8):

Equation 1

$$X = T - D$$

where:

X = industrial water use

T = total water use

D = domestic water use

The second equation determines industrial employment (Staley, 1960, p. 8):

Equation 2

$$M = \sum_{i=1}^{n} (a_i X / B_i$$

where:

M = industrial employment

ai = percentage of industrial water used in industry i ($i = 1 \ldots, n$)

Bi = gallons of water per employee in industry i;

X = industrial water use.

The third equation determines the amount of domestic water use. (Staley, 1960, p. 8).

Equation 3

$$D = (M + \lambda M + yM + \lambda yM),$$

where:

D = the amount of domestic water use

M = amount of industrial employment

y = induced employment

δ = consumption of water per person per year

λ = the dependent/employee ratio

He assumed: $y = 1$, or that each new industrial worker provided for one secondary employee, $\delta = 10{,}950$, and $\lambda = 1.5$ (1960, p. 8). Thus, the third equation can be written as follows (Staley, 1960, p. 9):

Equation 3'

$$D = 54{,}750\ M$$

He solved the simultaneous equations in the following manner (1960, p. 9). First, he substituted equation 3' for D in equation 1:

$X = T - 54{,}750M$; then, he substituted equation 2 for M to derive equation 4:

Equation 4

$$X = T - 54{,}750\ (a_1X/B_1 + a_2X/B_2 + \ldots + a_nX/Bn)$$

The solution to equation 4 is:

$$X = T/(54{,}750a_1/B_1 + 54{,}750a_2/B_2 + \ldots + 54{,}750a_n/B_n + 1)$$

This model is designed to tell how much industrial employment can be supported in a city with a given river flow. Given a rate of employment growth, it is possible to estimate when the maximum employment level will be reached. (Staley, 1960, p. 9).

Employment data was used by Hittman Associates (1969) to forecast water use by different industry groups. Water use per employee was the parameter they used to measure consumption. This approach is best suited for industries that receive most of their water from municipal utilities. Unfortunately, industries that require large amounts of process water usually develop their own sources of supply. (Hittman Associates, 1969, p. VI-1). The water use equations they used are (1969, p. VI-2):

$$\bar{q}_n = \bar{U}_n\ P_n$$

$$(q_n)_{mxdy} = (U_n)_{mxdy}\ P_n$$

$$(q_n)_{pkhr} = (U_n)_{pkhr}\ P_n$$

where:

$\bar{q}_n$ = average annual water requirement for industrial category n;

$(q_n)_{mxdy}$ = maximum day water requirement for industrial category n;

$(q_n)_{pkhr}$ = peak hour water requirement for industrial category n;

$\overline{U}_n$ = average annual water usage coefficient for industrial category n;

$(U_n)_{mxdy}$ = maximum day water usage coefficient for industrial category n

$(U_n)_{pkhr}$ = peak hour usage coefficients for industrial category n

P_n = water use parameter (category employment) for industrial category n.

The statistical models that were developed to project employment were based on data from the same sample of cities. The models were derived for two-digit standard industrial code categories. Because of difficulties encountered in collecting employment data, similar two-digit S.I.C. industrial categories were grouped together so that ultimately eleven groups were formed. (Hittman Associates, 1969, p. VI-6).

The following equations were used to project employment in each group. (Hittman Associates, 1969, p. VI-8):

$$IND_m/P = IND_m/P + \Delta t \; \Delta(IND_m/P)/\Delta t$$

$$IND'_m = P' \; IND'_m/P$$

where:

' = projected value

IND_m = employment in industrial group m

P = resident population

t = calendar year.

The employment change in the different categories contained in the major groups can be found as follows (Hittman Associates, 1969, p. VI-8): $EMP'_n = EMP_n \; IND'_m/IND_m$

where:

EMP_n = employment in category n, within indusgry group m.

Though employment data appears very helpful in explaining water use, other water forecasting approaches attempt to integrate many different economic, political, and social influences. Economic base studies have been proposed as methods of understanding the nature of growth in an area. This includes an understanding of the growth potential of industries present in an area and the attractiveness of the area to other industries (Sewell and Bower, 1968, p. 22). One such technique is the export-base approach. This technique identifies a region's major export oriented industries, their existing and potential markets, and their expected success in these markets. It also determines how much local service industry will be needed to support the exporting industries and the local population. (Howe, 1968, pp. 64-65). In such an analysis, it may be possible to predict a region's future industrial activity, and hence, project industrial water use.

Bower (1968) has attempted to identify the variables that establish water use in manufacturing. These variables are indicative of such things as the production process, raw materials employed, output, level of production, and pollution controls. These influences are presented in the following function (Bower, 1968, pp. 88-89):

$$Q_{It}, U_t, Q_{Et}, W_{Dt}, W_{Et} = f(C_I, PP - PM, RM, OR, R, MR, BP, C_E)$$

where:

Q_{It} = time pattern of water intake

U_t = Consumptive use

Q_{Et} = final effluent

W_{Dt} = waste load generated

W_{Et} = waste load in the final effluent

C_I = cost of intake water

$\frac{PP}{PM}$ = combination of production process - product mix

RM = nature of raw materials used

OR = operating rate

R = degree of recirculation

$\frac{MR}{BP}$ = possibilities of the recovery of materialsand by-product production

C_E = cost of handling and disposing of final effluent

The variables included in Bower's function can be grouped into different categories (Bower, 1968, p. 89). The first group is the technology of production and refers to how many steps are involved in the manufacturing process, and the effect of technology on production (Bower, 1968, pp. 90, 94). The second group is concerned with regional industrial location and the difference in the industrial environment between regions, including markets, raw materials, and transportation. (Bower, 1968, pp. 99, 103). The third group is in--plant water utilization variables. These variables determine the amount of water used in processing and cooling uses, the quality standards of the water required, and the amount of recirculation possible. (Bower, 1968, pp. 107, 117). The fourth group is the water environment. These variables include the availability of water effluent controls, and the availability of areas for the dumping of waste materials. (Bower, 1968, pp. 120-21). The final group is the influence of government policy on the cost of water and disposal of wastes. (Bower, 1968, p. 125).

Finally, a forecasting model put forward in 1951 by Elder also weighs many different variables, but these are more business oriented than the ones mentioned previously. This model attempts to explain all municipal water use and contains measures of residential, commercial, and industrial activity. It is based upon his observation of how water sales have fluctuated with changes in the state of the economy (1951, p. 129). To measure the effect of the economy on water use, he used the "Index of Business Activity in Southern California" produced by the Security First National Bank of Los Angeles (1951, p. 129).

> "This index is a weighted average of ten seasonally adjusted business series. With their respective percentage weights, these are as follows: department store sales, 15; building permits, 5; Los Angeles bank debits, 20; residential city bank debits, 5; agricultural city bank depits, 5; industrial employment, 20; industrial power sales, 13; railroad freight volume, 6; telephones in use, 7; and real estate activity, 4" (Elder, 1951, p. 129).

He correlated this index with per capita water production for the years 1928 to 1950, and derived the following equation (1951, p. 129):

$$W = 0.365\ I + 07;$$

where:

W = regional water production in gallons per person per day;

I = business activity index.

The coefficient of correlation for this equation was .94 ± .02. There was a lag of two years between the values for per capita water consumption and the business activity index. The effect of changes in business seem to take two years before it affects water consumption (Elder, 1951, pp. 129-130). It appears that if it is possible to forecast the economy, then one may be able to predict changes in industrial water demand.

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